SOUND WAVES

AND THEIR USES

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SOUND WAVES
AND THEIR USES

Six Lectures delivered before a "juvenile auditory" under the auspices of The Royal Institution, Christmas, 1928

BY

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To

Mollie, Elspeth,

Alison, and Mary

PREFACE

This book consists of the Christmas Lectures, substantially as they were delivered, although the treatment has been modified in some respects. It is likely to prove less entertaining to younger children, but more useful, I hope, to all who desire an introduction to recent developments of the subject. It may seem rash to offer a subject treated as recently as ten years ago by that master of the art of public lecturing, Sir William Bragg; but advance has been rapid and the choice of subject was encouraged by Sir William Bragg himself. A Bibliography has been added for the guidance of those who wish to read more widely.

A glance at the pages of the book will show how widespread was the help willingly and freely given by business firms and by individuals, but the gratitude of the lecturer is especially due to Sir William Bragg for constant encouragement and advice; to Mr. W. J. Green, Lecture Assistant at the Royal Institution, and Mr. J. Dear, Lecture Assistant at the Cavendish Laboratory, for invaluable co-operation and help in the preparation of lecture experiments; and to Dr. G. T. Bennett, F.R.S., for reading the proof and for many helpful suggestions.

A. W.

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Science of Musical Sounds—Dayton C. Miller (Macmillan Co., New York).
Figs. 4, 56, 67, 81, 84, 85, 86, 87, 88, 89, 90, 91, 92, 93.

Proceedings of the Physical Society of London.
Figs. 9, 10.

Acoustics of Buildings—Davis and Kaye (George Bell & Sons, Ltd.).
Figs. 22, 110, 111, 112, 113.

Acoustics of Buildings—Watson (John Wiley & Sons Inc., New York).
Figs. 114, 115.

Proceedings of the Royal Society of Edinburgh.
Fig. 28.

Proceedings of the Royal Academy of Sciences, Amsterdam.
Fig. 31.

Annales de l'Institut de Physique du Globe.
Fig. 32.

Proceedings of the American Philosophical Society.
Fig. 38.

The Philosophical Magazine.
Fig. 78.

Speech and Hearing—Fletcher (Van Nostrand Co. Inc., New York).
Figs. 69, 94, 95, 96, 97, 98, 100, 104, 105, 107, 137.

Proceedings of the Royal Society of London.
Fig. 102.

The Mechanism of the Cochlea—Wilkinson and Gray (Macmillan & Co., Ltd.).
Fig. 106.

CONTENTS

the other side. The result of a continuous turning of the handle is that waves appear to pass along the top of the model horizontally, while each ball is clearly seen to be moving up and down in a vertical path. The distance which a ball moves from its mean or average position is called the *amplitude*, and it is obvious that all the balls have the same amplitude. The number of complete vibrations executed in 1 sec.

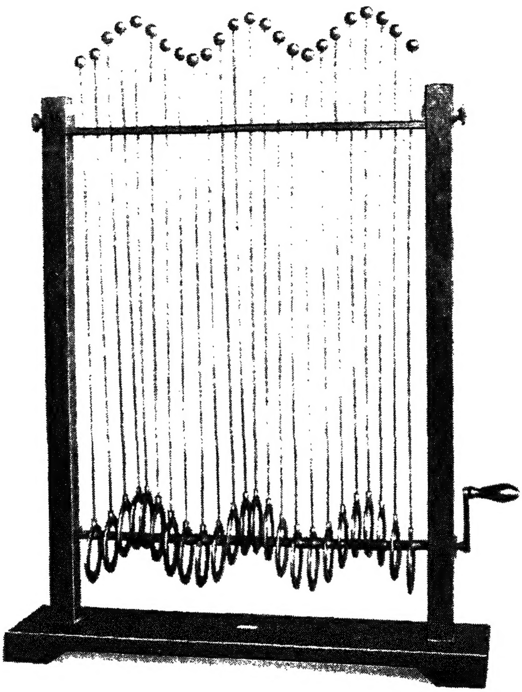

Fig. 1.—Wave Model

is called the *frequency*, and the distance between any two consecutive balls in the same stage of vibration is called the *wave-length*. Thus in the case of the waves illustrated by the model or in the case of water waves, the wave-length is the distance from crest to crest or from trough to trough.

A very important relation exists between the frequency, the wave-length, and the velocity, which may easily be deduced from the model and is true for all kinds of wave-motion. If we fix our attention on a ball which is at the highest point of its vibration and therefore coincides with the crest of the wave, and watch it while it performs a com-

plete vibration, we shall find that it now coincides in position with the crest of the next wave, the crest of the first wave having moved through one wave-length. If we call the frequency n, then in 1 sec. the ball will have described n complete vibrations and the original crest will be n wave-lengths away. It will thus have travelled a distance $n\lambda$, where λ is the wave-length; but since this is the distance travelled in 1 sec. it is the velocity of the wave, so that we find:

$$V = n\lambda$$

If we now turn to the model shown in fig. 2 we can illustrate some further properties of wave-motion. It consists of a row of

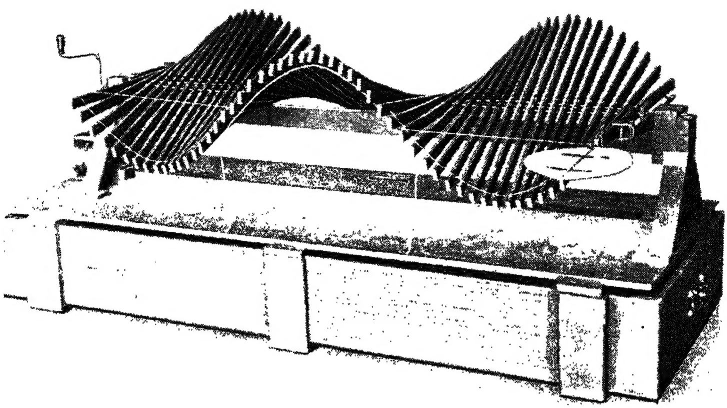

Fig. 2.—Vinycomb Wave Model

A series of wooden laths supported by a stretched horizontal wire passing through central perforations and by two long fine springs one on either side of the central wire.

wooden laths so connected that if one is disturbed its transmits its motion to the next, and so on. This model was designed by Professor Vinycomb and has been lent to us by the makers, Messrs. Griffin & Tatlock. It comes nearer to an actual wave than the model previously used, since the displacement is conveyed from lath to lath instead of being communicated separately to each as in the case of the balls. If the end lath is displaced we shall see a wave of displacement travel from end to end of the model. If the lath at the other end be fixed, we notice that the wave does not stop at this boundary but is reflected from it, travelling back again to the end from which it started. This illustrates the reflection of a wave which, for elastic waves, takes place not only at a rigid boundary but at any boundary which separates two media in which the wave travels with different speeds. Thus a sound wave may be reflected not only from a wall or

cliff but from a fog bank, the fog serving to make visible two regions of air in which the conditions of temperature and moisture are different, and in which, therefore, sound waves travel with different speeds. In the case of a wall, however, the reflection is almost complete, whereas in the case of a fog bank a considerable proportion of the energy passes on into the fog and only a fraction is reflected. A similar instance in the case of light waves is the reflection of sunlight from a glass window. When the sun is low the reflection is easily seen by observers at a considerable distance from the window, while people inside the room receive the light which has been transmitted and are hardly conscious that the brightness of the sunshine has been impaired at all. Let us now produce simultaneous displacements of the laths at the two ends of the model. Two waves immediately start towards the centre, meet, pass, and continue their journey unchanged. At the point where they meet the two waves are said to be superposed. They do not interfere with one another, but the displacement of any lath is the algebraic sum of the displacements due to each wave separately. Thus if both waves are produced by upward displacements, then where they meet the laths will have a double upward displacement; but if one wave carries an upward displacement and the other an equal and opposite downward displacement, then where they meet the laths will be undisplaced but the progress of the waves will not be arrested.

This superposition is a very important principle. In its application to sound waves it means that the air in a room is capable of carrying many waves at once, so that during an orchestral performance, for instance, the waves produced by the violins do not destroy the waves produced by the brass wind instruments, and we can listen to either at will. In the case of light it means that 500 people in a room can be looking at 500 different things, and the waves from each object will find their way to the corresponding eye without being affected by the other sets of waves. The phenomenon is sometimes known as interference, although it will be obvious from the explanation just given that the term is not very well chosen. It has arisen through concentrating attention on points in the medium where two or more simultaneous motions always annul one another, and the medium remains at rest.

This aspect of the phenomenon can also be illustrated by the model shown in fig. 2. Applying by means of clock-work a continuous vibration to the end lath and fixing the lath at the farther end, waves are transmitted along the model and reflected from the farther end. These two sets of waves become superposed so that some laths remain permanently at rest, while midway between these we have laths in maximum motion.

The way in which this so-called stationary vibration arises may perhaps be made more clear by referring to the diagram in fig. 3. Let the two thin lines represent two equal sets of waves moving in opposite

directions, and at the instant shown on the top line having their crests and troughs coincident. The heavy line shows the resultant displace-

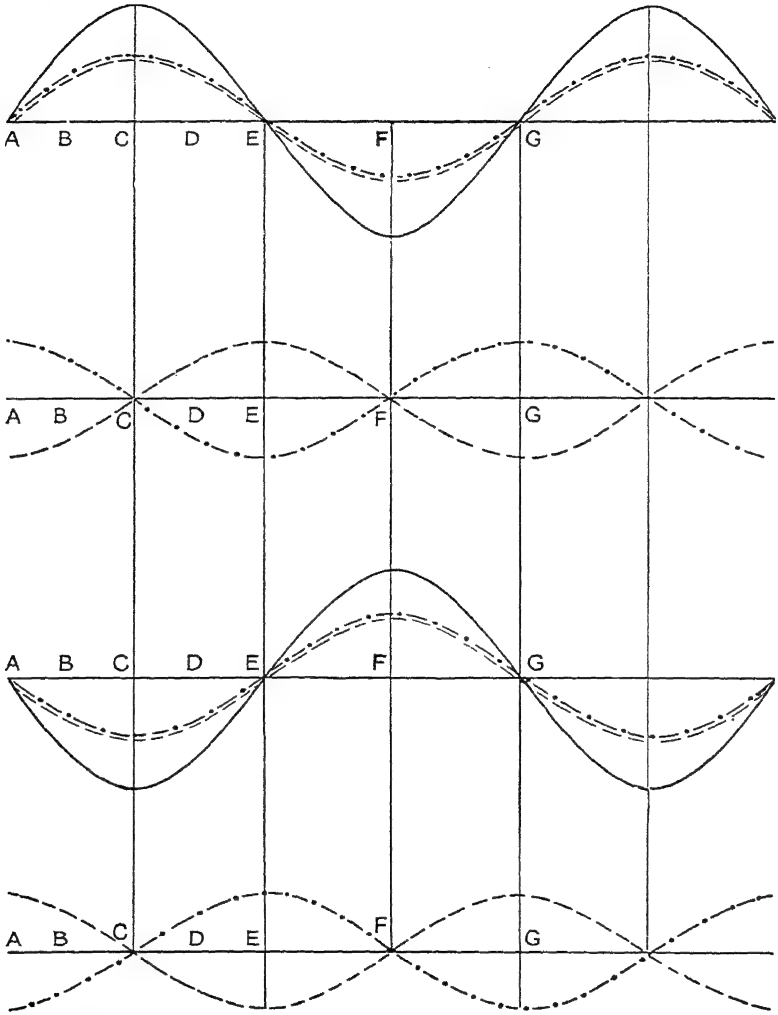

Fig. 3.—Stationary Wave due to two unequal sets of waves travelling in opposite directions

The broken line with dots represents waves travelling to the left. The broken line without dots represents waves travelling to the right. Four successive instants are shown.

ment of the medium. Subsequent positions of the waves and the resultant displacement of the medium are shown successively in the three lines below. It will be noticed that at the points A, E, G the displacement is always zero, either because the displacement due to each

wave is zero or because the displacements due to the two waves are equal and opposite. On the other hand at C and F the displacement is first a double displacement upwards, then zero, then a double displacement downwards, then zero again, and finally a double displacement upwards. At B and D the motion is similar but the amplitude is less. The points of zero motion are known as *nodes*, and the points of maximum motion as *antinodes*.

So far we have been considering models which illustrate transverse waves, that is to say, waves in which the motion of the particles of the medium is at right angles to the motion of the waves. There is another type of wave, however, the type to which sound waves really belong,

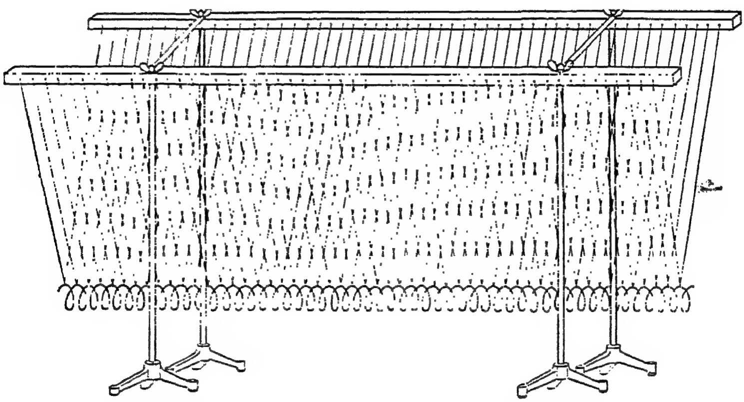

Fig. 4.—Suspended horizontal spring for illustrating the propagation of longitudinal waves, i.e. waves of compression and rarefaction

in which the motion of the particles of the medium is a to-and-fro vibration in the direction in which the wave is travelling. This type may be very simply illustrated by a long spiral of copper wire (fig. 4), the turns of which are suspended by two threads from a wooden frame, so that the spring hangs horizontally. If the diameter of the spiral and the thickness of the wire are suitably chosen, then if one end of the spring be struck with the hand, a slow wave of compression travels to the farther end of the spring. This wave is produced by a to-and-fro vibration of the turns of the spring. If the other end of the spring be either free or fixed the wave will be reflected. If similar waves are started simultaneously from opposite ends, then as in the case of the previous model they pass through one another and continue their journey unchanged.

With this model also we can illustrate stationary waves by applying a to-and-fro motion to one end of the spring while the other is held fixed. By careful timing of the vibration the spring can be made

to break up into a well-marked series of nodes and antinodes, the coils at the antinodes moving backwards and forwards between two adjacent nodes.

As the longitudinal type of vibration is the one with which we have to deal in sound waves, it may be worth while to give one further illustration of it in a way which enables us to study the motion in detail.

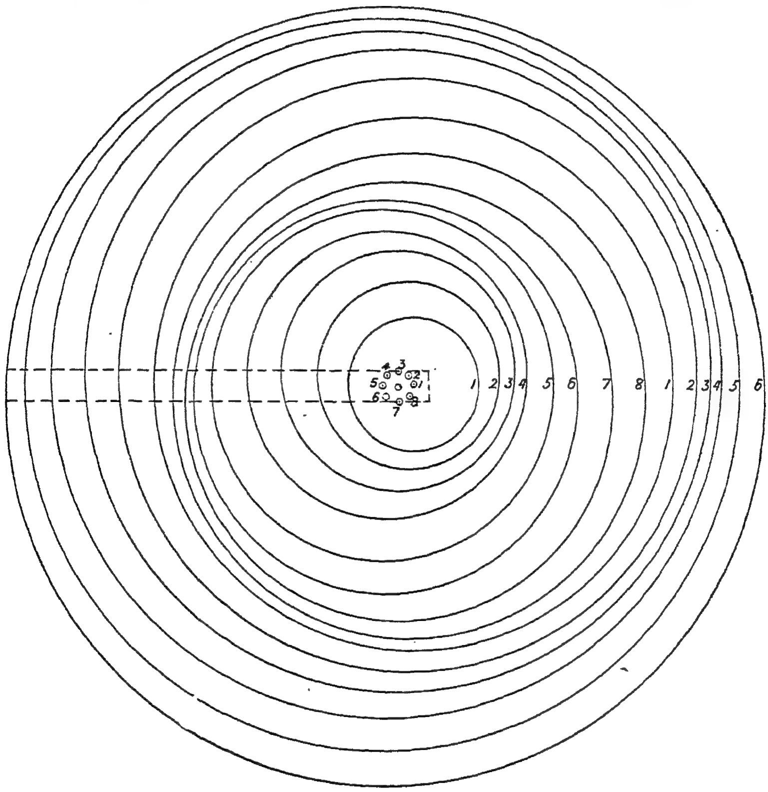

Fig. 5.—Crova's Disc

The numbers show the corresponding centres and circumferences of the circles.

Fig. 5 illustrates the arrangement known as Crova's disc. Circles of radii increasing by a uniform amount are drawn with the equidistant points shown on the small circle as centres. If now a slit be placed along a radius as shown by the dotted lines and the disc rotated, waves will appear to pass along the slit. For purposes of projection the circles are drawn on glass and the arrangement placed in the projection lantern. The lines crossing the slit may be taken to represent invisible boundaries between layers of air through which sound waves are being

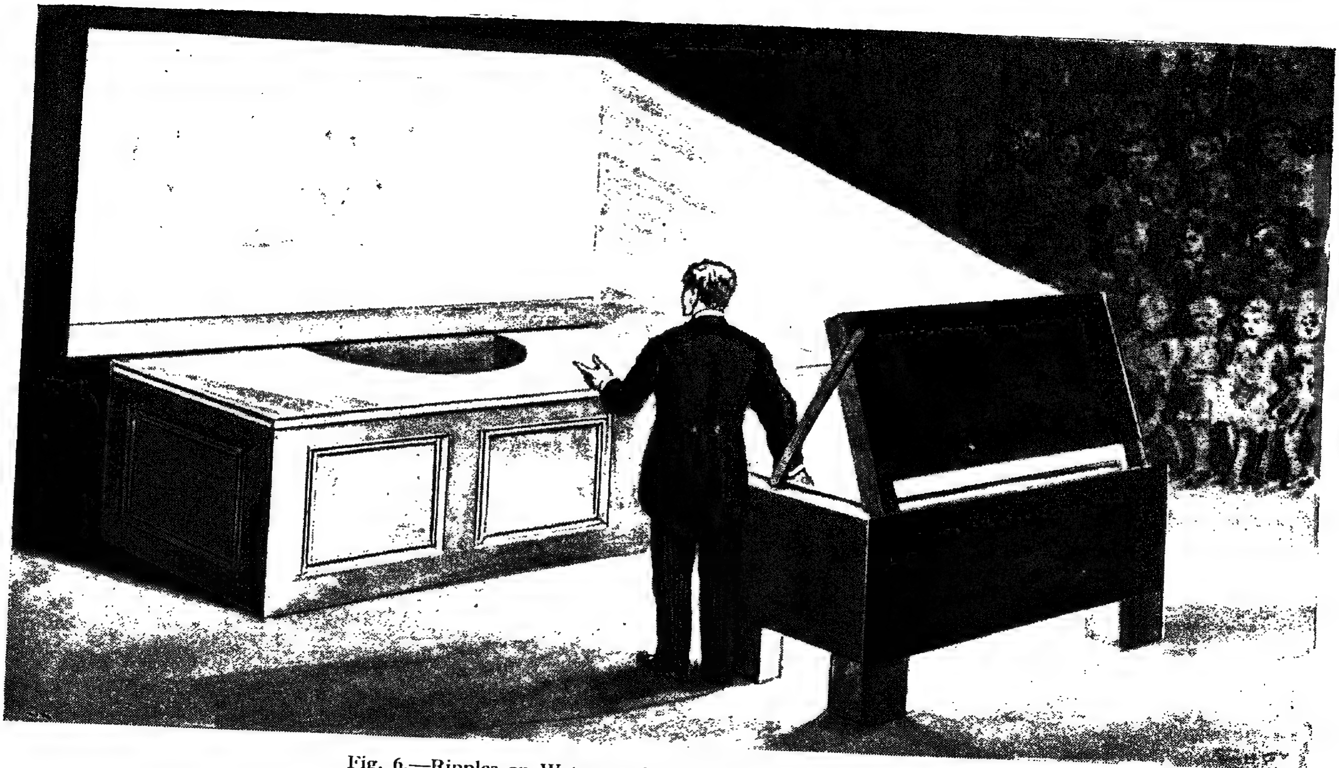

Fig. 6.—Ripples on Water passing each other without interfering

propagated. Where the distance between the lines is small the air will be compressed; where it is rather large it will be rarefied. If we fix our attention on any particular layer, say the layer which is most compressed, and move the model slowly, we shall see that the compressed layer is moving forward in the direction of the wave and gradually expanding. Its forward motion becomes slower and ceases altogether when its density becomes normal (i.e. at its average width). As it becomes rarefied it moves backward with increasing velocity, until when it has its greatest width (corresponding to greatest rarefaction) it is moving backwards with its greatest speed. Still moving backwards but with gradually diminishing speed it becomes less rarefied, until when its density is normal it is again at rest. It now begins to move forward, its density gradually increasing, until it comes to the point at which its density and forward motion are again a maximum, which is the point from which we started. A similar disc representing stationary vibration in air has been devised by Professor Cheshire, and it enables us to study in the same detailed way the changes which take place in the air when in this kind of vibration.

The Ripple Tank.

A very beautiful and interesting method of illustrating the properties of waves consists in using, for the purpose, ripples travelling on the surface of water. These ripples have the advantage that they are easily produced, and may be found to add a new interest to bath night. They are most easily observed by an audience if produced on the surface of water in a glass-bottomed tank, so that they may be illuminated by light from below and projected on to a screen (fig. 6).

In dealing with waves it is sometimes convenient to speak of them in terms of the "ray". Indeed, in the case of light waves, our first introduction to the subject is usually the study of rays. Now a ray is merely the path along which a particular part of the wave moves. When a line of men are marching, the line may be thought of as the wave and the path of each individual man as the ray. In most drill manœuvres every man is expected to move at right angles to the line, and in the case of wave-motion that is what we ordinarily find; the ray is perpendicular to the wave-front. Bearing this in mind, let us place in the tank a straight piece of wood to act as reflector, placing another piece of wood at an angle to the first and oscillating it gently. A set of straight ripples (fig. 7) is propagated,

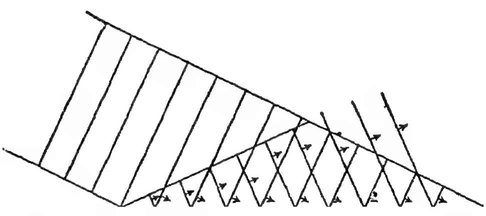

Fig. 7.—Reflection of straight ripples from a straight reflector

strikes the reflector, and comes away from it as a set of ripples, making with the reflector an angle equal to that made by the incident ripples. Replacing the straight reflector by a piece offering a concave circular surface and directing our straight ripples into it, we shall see that the reflected waves are converged or focused approximately to a point (fig. 8). This point, as a matter of fact, bisects the radius of the reflecting surface. Removing the wood used to produce the straight ripples, and touching the point to which the circular surface converged the straight ripples, we produce a set of circular ripples which after reflection are straight. This is the principle of the headlight or searchlight reflector, from which the light waves issue as a parallel beam and not a diverging beam.

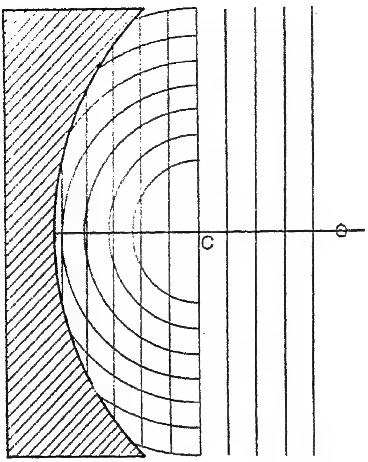

Fig. 8.—Reflexion of straight ripples from a circular reflector and conversely

These experiments on reflected ripples have an interesting and practical application to the acoustics of buildings. A longitudinal

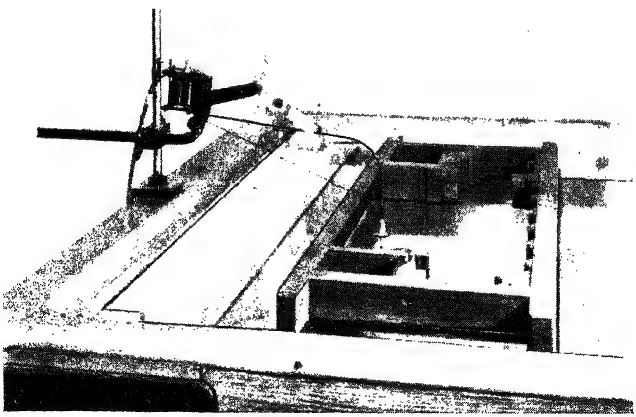
Fig. 9.—Ripple Tank Model as used at the National Physical Laboratory

section of a building is modelled in wood of sufficient thickness to project above the surface of the water. Ripples are then started at a

point corresponding to the position of a speaker, and the progress of the direct and reflected ripples can be watched as they spread through the space enclosed by the model. The ripples can also be photographed at short intervals and this gives a permanent record which can be studied at leisure. Fig. 9 shows a model in position in the tank, with

a. Gallery under separate ceiling

b. Gallery under main ceiling

Fig. 10.—Photographs of Ripples inside tank models

the dipper used for producing ripples as in the apparatus set up in the National Physical Laboratory. Fig. 10 shows photographs illustrating the practical application. Writing of these photographs, Dr. A. H. Davis says: " They show the desirability of putting the gallery under the main ceiling of the council chamber concerned. If ceilings are low enough, they do not give rise to distinguishable echoes; indeed, reflections of sound from them contribute usefully in raising the level of loudness in regions reached. Ceiling reflection is particularly desirable in large council chambers where speeches may be delivered from any

part of the floor, for no other reflecting surface would be equally effective for all speakers. In the photograph, fig. 10(*b*), we see the ceiling reflection spreading to benefit people even in the rear of the right-hand gallery; in fig. 10(*a*), where the roof has been modified so that the gallery is under a separate ceiling, this useful reflection to the back is cut off."

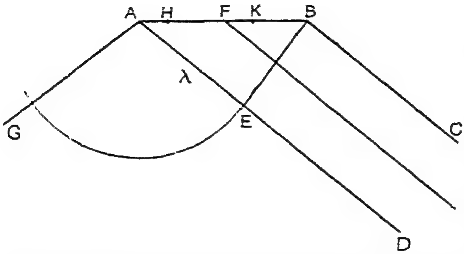

Fig. 11.—Application of Huyghens' Principle to spreading of waves from a narrow slit

The diffraction of waves issuing from a slit can also be shown, although this particular property of wave-motion is better illustrated by using a continuous series of ripples rather than the short train of ripples produced by the movement of the wooden bar as we are using it at present.

If the line AB (fig. 11) represents a slit upon which straight waves fall parallel to AB, then we can think of each point on the wave as it arrives at AB as giving rise to a new set of waves spreading forward into the space beyond the slit. This principle was first enunciated by Huyghens (1629–95) and is called Huyghens' Principle. If we consider the direction to a distant point given by AD and BC, then the waves coming from the point A in this direction will be behind those coming from the point B by a distance AE, where BE is perpendicular to AD. Suppose this distance to be one wave-length. Then in this case waves coming from the middle of the slit F will be half a wave-length behind those coming from B, while those coming from A will be half a wave-length behind those coming from F. Thus to each point in AF (say H) there corresponds a point in FB (say K) such that the difference in path between the two sets of waves is half a wave-length, so that in the direction considered the crest of a ripple from one point will coincide with a trough from the other, and there will be hardly any ripple motion propagated in this direction. If we consider directions still more oblique some ripple motion is propagated, but exact calculation shows that the ripples spreading out from the slit are

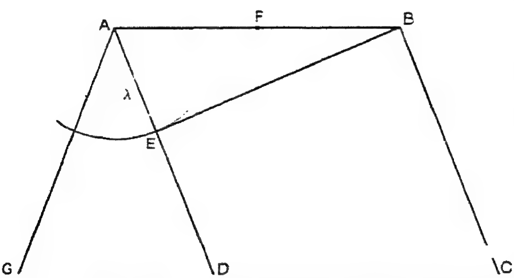

Fig. 12.—Application of Huyghens' Principle to spreading of waves from a wide slit

almost entirely confined between the direction BC and a direction AG, making the same angle with the normal to the slit. Compare this diagram with the corresponding one in fig. 12 in which the slit is twice as wide, and we shall see that the divergence of the ripples must be much less if the wave-length is the same. Thus for a given wave-length the wider the slit the less is the divergence of the ripples, and the narrower the slit the wider the divergence of the ripples. It will be seen that if the slit is one wave-length wide or less the ripples must spread in every direction on the other side of it. This discussion is illustrated by experiments in which, placing two wooden blocks some distance apart (fig. 13), we see that the ripples pass through the slit and continue as a set of straight ripples with little divergence. Placing the blocks close together (fig. 14), we find that the ripples spread out as a nearly circular system diverging in every direction.

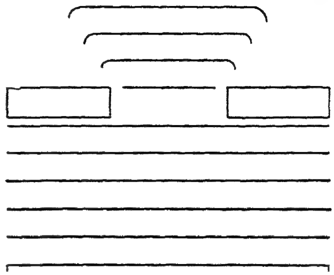

Fig. 13.—Passage of Ripples through a wide slit

The property of diffraction is further illustrated by putting in the path of the straight ripples an obstacle several wave-lengths wide. We notice some bending of the ripples into the rear of the obstacle, but a well-marked quiet region or shadow protected by the obstacle. On the other hand, taking a small obstacle, we notice that the shadow practically disappears and the ripples bend round it and continue as if the obstacle had not been there at all. If we now incline the tank so that the depth of water varies, we can illustrate the property of refraction which arises when the velocity of waves is not the same at all points in the medium. The velocity of a ripple varies with the depth. If, therefore, we start a set of straight ripples by using the block of wood placed so that one end is in deep water and the other in shallow water, then the ripples, instead of continuing as a system of straight lines parallel to the block, wheel round and tend to become parallel to the edge of the water. This is due to the fact that the end in the deeper water travels faster and so travels farther in a given time. We can see the

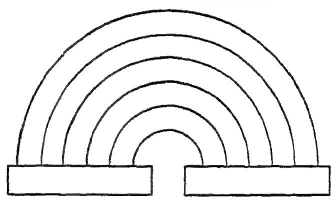

Fig. 14.—Passage of Ripples through a narrow slit

same phenomenon on a large scale when waves are coming in on a shelving beach. Whatever direction the waves may have in the deep water, they arrive at the beach with the line of the wave almost parallel to the line of the beach (fig. 15).

Some of the properties of ripples may be more conveniently studied if we produce a continuous series of ripples, which we can do by having a wire attached to the prong of a tuning-fork which is maintained in vibration electrically. The wire is arranged so that its point just touches the surface of the water in the tank. The vibration of the fork moves the point up and down and a series of circular ripples spreads out from it. By having two parallel wires a few centimetres apart, both attached to the same prong, and fixing across them a thin strip of wood which just touches the surface of the water, we can arrange to produce a set of straight ripples. In order to make these ripples still more easy to observe, we can arrange to illuminate them with light which is intermittent. If the flashes of light are correctly timed, so that in the interval between two flashes one ripple moves into the exact position occupied by its predecessor at the preceding flash, then we shall have a modification of the game known as "grannie's steps": every time we see the ripples they will appear to be steady and in the same position. If the flashes occur just too slowly the ripples will appear to move slowly forward; if the flashes are just too rapid they will appear to move slowly backward. Interrupting the beam of light by the revolution of a perforated disc driven by a motor, we can adjust the speed of the motor so as to get the appearance of a very slow motion which can be studied at leisure. Fitting to the wires our thin strip of wood we produce a set of straight ripples, and inclining the tank we at once get the phenomenon of refraction showing very distinctly. Using the different sized obstacles and the different sized slits we illustrate diffraction as before. Removing the strip of wood and leaving the two wires touching the water surface, we get two circular systems of ripples interlocking. Owing to the superposition of these two systems the water surface is divided up into places of maximum motion or antinodes, and places of minimum motion or nodes. These nodes and antinodes are distributed as shown in fig. 16.

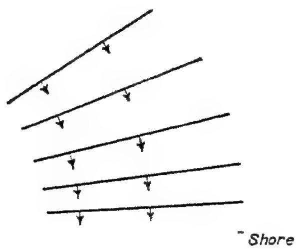

Fig. 15.—Refraction or change of direction of waves coming in on a shelving beach

This figure is copied from the published lectures of Thomas Young (1773–1829), who first gave a clear statement of the principle of interference of waves and successfully demonstrated it for light waves.

A and B are the two sources, and it will be seen that along lines emerging from the diagram at C, D, E, and F, we have crests from one source falling on troughs from the other and vice versa, while between these radiating lines we have others where troughs and crests respectively coincide.

As this interference pattern is itself a steady pattern, it is more easily observed if we stop the motor and examine the ripples with a steady illumination. The two sets of ripples now move rapidly through one another but the steady pattern remains fixed in position. Here again we have a case of stationary vibration due to two equal sets of waves. Nor need we have two coupled sources as in this case. Bending one of the wires so as to remove it from the surface of the water, and

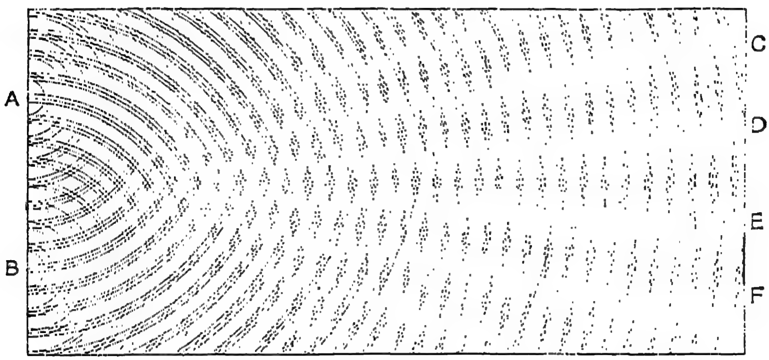

Fig. 16.—Interference or superposition drawn for two sets of ripples originating at A and B

placing a straight piece of wood in the neighbourhood of the point of the other wire, we get superposition of the direct and reflected waves and an interference pattern which is identical with half of the pattern previously observed. If we place the wood so that its perpendicular distance from the point of the wire is half the original distance between the two points, we may think of the superposition as due to two sets of waves, one coming direct from the wire as source and the other from the image of this source formed by reflection at the straight piece of wood.

Sensitive Flame Experiments.

And now we pass to another experimental method of illustrating properties of wave-motion more closely related to the main subject of these lectures. Sound waves show many of these properties less easily in lecture experiments because of their great length. The wave-length of a ripple is a few millimetres, while the wave-length of a sound wave measured from compression to compression may be several metres. It is possible, however, to produce short sound waves by using a

whistle or bird-call as source, or as we shall do here by using an ordinary telephone diaphragm operated by a valve oscillator, and giving a frequency of about 20,000 and a wave-length of about a centimetre and a half. The electrical connexions are shown in fig. 17, which is taken from a paper by S. R. Humby in the *School Science Review*. To detect these waves we use a sensitive flame (fig. 18). If a piece of glass tubing be drawn down to a fine nozzle and gas be passed through it and lit, then as the pressure of the gas is increased the flame becomes taller and taller. Presently, however, the character of the flame changes: instead of burning quietly it roars and drops considerably in height. This is due to the fact that for small velocities of the gas through the tube the motion is stream-line. The motion of the small portions of

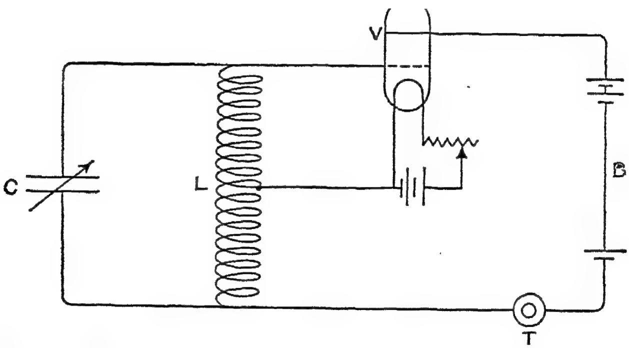

Fig. 17.—Electrical connexions for a valve-operated telephone diaphragm used as a source of high-frequency sound waves

C is a capacity, L a self-induction, V a valve, B the battery, and T a telephone.

gas is orderly like a procession. As the velocity increases, however, this type of motion breaks down at a certain definite value of the velocity, eddies begin to form, and the motion becomes disorderly like that of a crowd. Just before the stream-line motion breaks down, the flame is very sensitive and the slightest motion at the nozzle causes the motion to pass from one type to the other, with obvious results on the flame. The flame, of course, merely indicates the kind of motion, and the same effect can be produced on a jet of smoky air as was shown over a century ago by Thomas Young.

If we now adjust the flame so as to make it sensitive you see how easily it is disturbed. The slightest hiss makes a roar. It responds to the ticking of a watch two or three centimetres away. The rattling of keys, even in the pocket, produces a strong disturbance, while "banging a saxpence" on the table nearly extinguishes it. If, following the example of Tyndall, I recite to the flame a passage from Spenser's "Faerie Queene", you notice how the flame is modified by the sounds and how in particular it picks out the sibilants. If I take two brass

tubes about 2 cm. in diameter and place them with their ends close together, as shown in fig. 19, then by directing a source of sound into the remote end of one tube and placing the sensitive flame near the remote end of the other tube, we can use a board to reflect the waves from one tube into the other. In order to shield the sensitive flame the nozzle is placed in the tube, coming through a hole on the under side and the flame coming through a hole on the upper side. A very small displacement of the board throws the arrangement out of adjustment, showing that the law of regular reflection is obeyed.

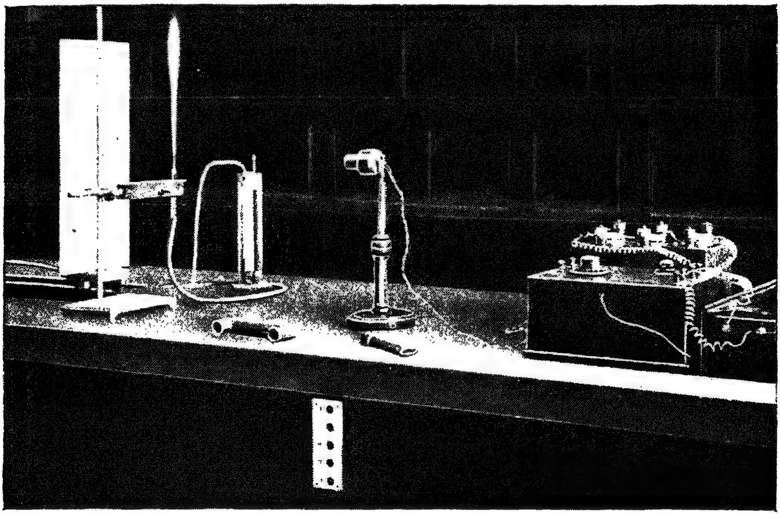

Fig. 18.—Sensitive Flame, showing reflecting board, manometer for measuring gas pressure, valve-maintained telephone, and attachments for showing superposition from two sources and diffraction from elliptical horn

If now I fit over the source a T-shaped brass tube with two apertures, then the waves issuing from these two apertures will produce an interference pattern exactly similar to that seen on the surface of the water when disturbed by the two wires. Directing this towards the sensitive flame and then swinging it gently round, I sweep the system of nodes and antinodes across the flame, and you see it respond where the air is in motion and remain still where the air is at rest. Removing the T-piece I direct the telephone towards the flame, and place close behind the flame a vertical board on a sliding stand. The air between the board and the telephone is now broken up into a system of nodes and antinodes, produced by the direct waves from the telephone being superposed on the reflected waves from the vertical board. This system of nodes and antinodes moves with the board, so that drawing the board back the flame is alternately agitated and

calm. If I count the number of nodes through which the flame passes and the distance which the board is drawn back, dividing the distance by the number of nodes we obtain the distance between two nodes, which is half the wave-length of the waves. This turns out to be rather over a centimetre. Removing the board from the stand, and holding it horizontally between the telephone and the flame and a little below the line joining them, we can get the superposition at the flame of two sets of waves, one coming directly from the telephone and one reflected from the board. As the board is moved up and down the flame reveals the presence of the nodes and antinodes.

This experiment is exactly analogous to the experiment in optics

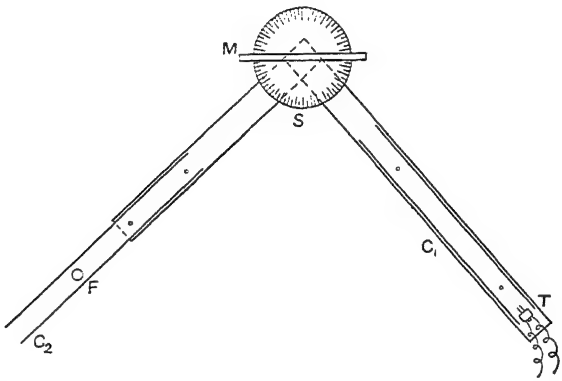

Fig. 19.—Diagram of apparatus for illustrating the reflection of sound waves

C_1, C_2, brass tubes; T, telephone; F, sensitive flame; S, Protractor for measuring angles; M, reflecting surface.

known as Lloyd's single mirror, where interference fringes are produced by having a small source of light very close to the plane of a mirror. The fringes may be treated as if they were due to interference between the real source and its image in the plane mirror. It is also the basis of a method of measuring the height of the Heaviside layer in the atmosphere which acts as a reflecting surface for wireless waves. Interference is produced between waves received directly at a station and waves which have been reflected from this layer, and if the wave-length can be varied the observations enable us, as Professor Appleton has shown, to calculate the height of the layer.

Turning to the property of diffraction, we can illustrate this by fitting over the telephone a small horn of elliptical section. We direct this towards the flame with the long axis horizontal, and swing it slowly round in a horizontal plane until we reach a point at which the flame just ceases to respond. Keeping the direction of the axis of the horn the same, we twist it round its axis through a right angle, bring-

ing the short axis of the ellipse horizontal. The flame responds at once, verifying our rather surprising conclusion that waves spread more when they issue from a narrow aperture than when they issue from a wide one. Removing the horn we direct the telephone once more towards the flame, and place between the two a circular disc with its centre on the line joining them. Although the flame is now at the centre of the sound shadow produced by the disc, it still responds strongly. This is due to the fact that the sound waves bend round into the shadow, and that for a point on the axis of the disc all the paths of the waves from the telephone round the edge of the disc to this point are equal, so that the waves reinforce one another. Just off the axis this is no longer true: waves coming round one side of the disc have a longer path than those coming round the other side, and consequently they no longer exactly reinforce one another. If the disc is set swinging as a pendulum, it will be noticed that the flame responds every time the disc moves through its middle position and is still for the rest of the swing, showing that the axis of the disc gives considerable sound intensity although right at the centre of the shadow. This is the sound analogy of the experiment of Fresnel and Arago, in which the shadow of a small circular disc is thrown by an illuminated pinhole and is found to show a bright spot right at the centre.

Pressure of Sound Waves.

Waves have another very important property which we have so far not considered. If a set of waves fall on a surface they exert a pressure on it. This pressure has a certain value if the waves are completely absorbed by the surface, and is twice as great if the waves are completely reflected. Thus waves carry momentum. If we arrange two large concave mirrors with an electric spark gap at the principal focus of one and a delicately pivoted set of small vanes at the principal focus of the other, then a series of heavy sparks may be made to pass across the gap, producing a loud cracking noise, the sound waves from which are reflected by the first mirror as a parallel beam, fall on the second mirror, and are converged to its focus. If these are directed on to the vanes on one side of the pivot the vanes reveal the pressure by getting into rotation. If we now move slightly the stand carrying the pivot so that the sound waves are focused on the vanes on the other side of the suspension, the vanes come to rest and begin to move in the other direction.

Photography of Sound Waves.

There is still another way in which the properties of sound waves may be investigated. The waves may be photographed and their successive positions revealed. In photographing these waves we are confronted by two difficulties, the high velocity of the waves and their

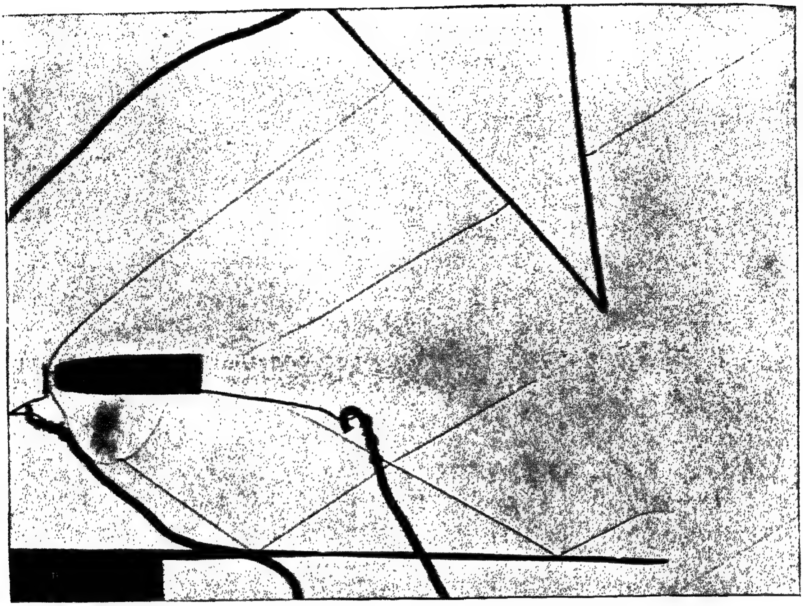

Fig. 20.—Rifle Bullet photographed while in flight by C. V. Boys

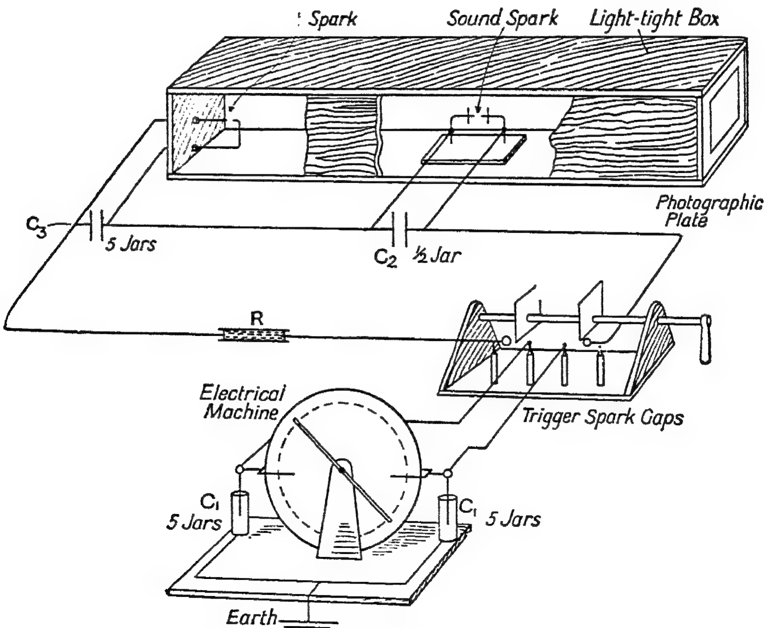

Fig. 21.—Apparatus for photographing sound waves used at the National Physical Laboratory for studying the reflection of sound inside a building

comparative invisibility. The first of these difficulties is overcome by making a very short exposure. No camera shutter can move fast enough for our purpose, as the waves are travelling at a speed of 1100 ft. per second. An electric spark, however, produces a flash of extremely short duration, and when photographed in the light of this without a shutter at all even very rapidly moving objects appear at rest. The other difficulty is overcome by taking advantage of the fact that compressed air has a greater refractive index than normal air, while rarefied air has a smaller refractive index. This means that the velocity of light in air varies with the density of the air, so that rays of light are bent from their path in passing from air of normal density to air which is either compressed or rarefied. It is this property which produces the shimmering of objects seen through rising currents of warm air on a hot day. Thus if we produce a sharp sound and follow it at a very short interval by an electric spark, we can throw a shadow of the wave on a photographic plate and register it there. This is the process which was used by Professor Boys for registering the air waves produced by a flying bullet (fig. 20), and it has been used by several experimenters to photograph the reflection and refraction of the sound waves produced by an electric spark. An interesting and recent application of the method is its use in connexion with the reflection of sound inside a building. Just as in the case of the ripple

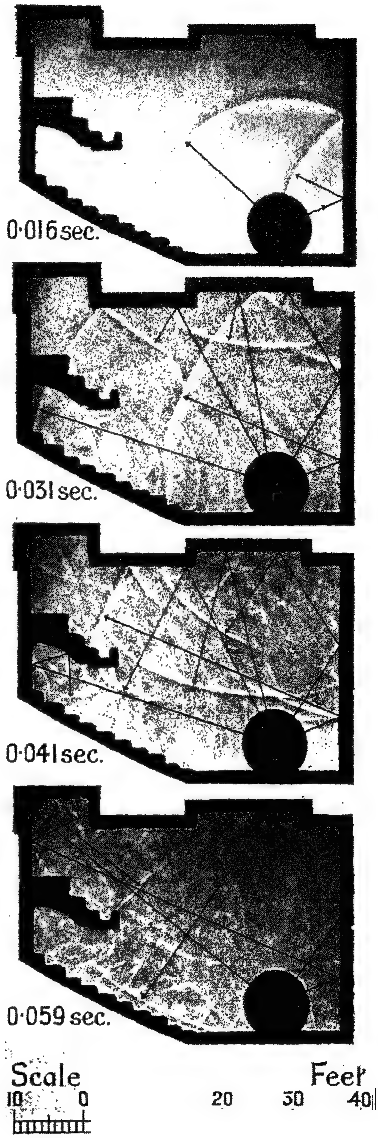

Fig. 22.—Sequence of sound-pulse photographs relating to the Royal Institution Lecture Theatre

tank we can study the reflections of the ripples produced by a longitudinal or other section of the building, so we can produce a crack from an electric spark at a suitable point in a similar model and photograph the reflected waves at successive short intervals after the production of the sound. This method is now applied at the National Physical Laboratory as part of its routine work. The apparatus is shown in fig. 21. The electrical machine with Leyden jars attached so as to give large capacity, charges up the two trigger spark gaps shown. In these two gaps are glass plates which by rotation of the handle on the right can be removed from the gaps as shown in the diagram. When they are removed a spark passes in two places. One of these sparks is the source of light, the other the source of the sound. By putting a capacity across the light spark gap considerably greater than that across the sound spark gap, the light spark is slightly delayed, so that it catches the sound a fraction of a second after it has started.

Fig. 22 shows a series of photographs, obtained by this method, of the reflected sound waves inside a model of the longitudinal section of the lecture room of the Royal Institution. The second photograp of the series shows very beautifully a succession of reflected wave from the tier of seats. The black circle indicates the position of th source, which has a screen placed to shield the plate from the ligh coming from the sound gap. The fine lines indicate the paths of rays corresponding to the different wave-fronts.

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LECTURE II

Signalling in Air and Water

Fog Sirens.

The transmission of sound signals by air has long been of considerable importance, especially in connexion with shipping. Round our coasts points of danger are marked by lighthouses, the light from which can, in clear weather, be seen for several miles. When the atmosphere is at all hazy, however, the visibility of these lights rapidly becomes less, and in a fog they may be invisible at a few hundred yards. In these circumstances the duty of warning the navigator has to be taken up by some kind of sound signal, and so very powerful sources of sound have been set up at these points. They usually consist of some form of siren, a blast of compressed air being emitted intermittently by slots in a revolving cylinder. Fig. 23 shows the siren in use at St. Catherine's Point. Fixed and revolving cylinders each have two corresponding rows of slots. In the upper rows the slots are more closely spaced and give a higher note. Every time the slots on the fixed and revolving cylinders coincide, air is driven through at high pressure and a note is produced by the train of compressions thus generated. In a modification known as the diaphone the slots are periodically covered and uncovered by the movement of a solid piston.

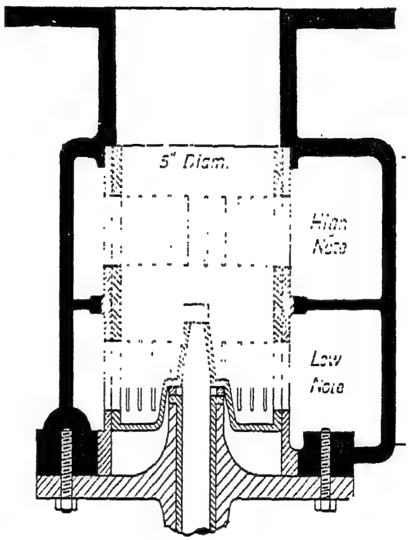


Fig. 23.—St. Catherine's Double-noted Siren consisting of a fixed and a rotating cylinder with two rows of slots in each similarly situated and spaced

In spite of the large amount of energy which has to be put into these sirens, there are occasions when the range of audibility seems

ridiculously small. Knowing the energy input and the sensitiveness of the ear, we may calculate the range of audibility of one of our big fog sirens, and we shall find it come out in hundreds or even thousands of miles. This result is of quite a different order from the range of audibility actually observed. When we come to investigate the reasons for this discrepancy we find that an obvious factor is the efficiency or inefficiency of the source of sound. Only a fraction of the mechanical energy used by a source is actually transformed into sound. The efficiency of various sources of sound has been investigated by Webster, and the following table is taken from one of his papers.

Name of Source.	Energy Input.	Sound Output.	Efficiency.
Cornet	$6 \cdot 7 \times 10^5$ erg/sec.	$7 \cdot 7 \times 10^2$ erg/sec.	0·0011
French horn	12·5 ,,	47·3 ,,	0·0038
Bombardino	3·2 ,,	123·1 ,,	0·0127
Saxophone (soprano)	22·0 ,,	19·7 ,,	0·0009
Clarinet	7·3 ,,	30·7 ,,	0·0042
Oboe	5·9 ,,	0·3 ,,	0·00005
Voice	11·6 ,,	110·0 ,,	0·0095
Violin	4·8 ,,	2·5 ,,	0·00052

It will be noted that the most efficient source is the bombardino, followed pretty closely by the human voice, but it is a sobering reflection for the singer that only 1 per cent of his or her energy is actually transformed into the sound which charms the audience, while 99 per cent runs to waste. The low efficiency of the oboe is quite remarkable.

It is, of course, a well-known fact that the range of audibility is not only unexpectedly low but very variable. As we listen to a source of sound we are conscious of large and rapid variations in its intensity. Tyndall drew attention to the part which a lack of homogeneity in the atmosphere must play in audibility. We have seen that wave-motion is reflected when it meets a boundary between two portions of a medium in which it travels with different speeds. Now the velocity of sound in air depends on the temperature of the air and on the amount of moisture it contains. The rising of hot air to mix with cooler air above when the sun is beating on the ground causes just this lack of homogeneity, and it reveals itself to our eyes by the shimmering of the outlines of objects due to refraction of light waves. The reflection of sound due to a similar cause may be fairly copious. This was proved by observations of Tyndall, in which he obtained pronounced echoes from the edge of a fog bank where presumably there was a sudden change in the amount of moisture held in suspension. He came to the conclusion that what he called flocculence of the atmosphere due to the mixing of air at different temperatures and carrying different

amounts of moisture was one cause of reflection and scattering of sound, and therefore of diminished range of audibility.

A more potent cause of the low range of audibility is probably the effect of wind gradient as pointed out by Reynolds. We are all familiar with the fact that sounds seem to carry better with the wind than against it, although we are probably not all aware of the fact that this effect depends on wind gradient. The air in contact with the earth is retarded in its motion, with the result that wind velocity always increases as we rise from the surface of the earth. It is this change in wind velocity which is the effective factor and not the velocity of the wind itself. If the wind blew at the same speed at all heights above the earth it would be practically without effect on the transmission of sound.

The way in which sound waves are affected by wind gradient is shown in fig. 24. The waves, but for the wind, would appear in the diagram as semicircles surrounding the source. They are actually distorted as shown, the tops being carried forward more than the lower edges. If now we remember that the sound rays are always perpendicular to the waves, we see that to windward the rays are directed upwards and tend to leave the surface of the earth, while to leeward they are bent down and so directed along the ground. This, then, is a case of refraction similar to that which we studied in the case of water ripples, and the relation between the two phenomena will become still clearer when we realize that the diagram is actually a sketch, made by Reynolds, of the ripples spreading out from drops falling into a stream which flowed past a vertical wall. Near the wall the velocity of the stream is retarded, so that farther from the wall it moves more rapidly, and what would be a semicircular set of ripples if the water were at rest becomes the set of ripples actually shown in the diagram.

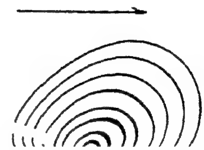


Fig. 24.—Drawing made by Osborne Reynolds of semicircular ripples distorted by the flow of water past a wall; used to illustrate the distortion of sound waves by a wind gradient

That this is actually what happens was demonstrated by Reynolds, using an electric bell placed one foot from the ground in a large field. Lying full length on the ground and wriggling out to windward, he ceased to hear the sound at 20 yd. distance. Raising his head he recovered the sound, but with his head at 3 ft. from the ground lost the sound again at 30 yd. distance. Standing up, the sound was again heard, but as he walked away he lost it at 70 yd. distance, his head now being 6 ft. above the ground. At still greater distances the sound could be heard at full intensity by climbing a pair of steps. Thus the effect of wind gradient is to deviate the sound rays, and the bad audibility against the wind with which we are all familiar is due to the fact that the sounds are passing above our heads.

Another important point which emerged from these experiments

was that the sound to windward was even stronger than that heard at the same distance to leeward, an effect due to the fact that to leeward the sound was kept close to the ground and lost more by friction. This was illustrated also by the observation that when the field was covered with snow audibility to leeward was greatly improved, the smooth surface of the snow absorbing less sound by friction than the irregular grass surface which it covered. This, no doubt, accounts also for the good audibility of sounds heard over water.

It will be observed that this refraction of sound is the property utilized by the sportsman in approaching his prey. If he approaches down wind the sounds due to his movement are refracted downwards and correspondingly well heard. If he approaches up wind the rays are refracted upwards and audibility on the ground is bad. The handicap under which the sitting bird labours will be realized when we

Fig. 25.—Refraction of sound rays from a source S on the ground due to a temperature gradient in the atmosphere in which the warmer layers are below. The waves are inaudible to an observer at O.

think how close to the ground its head usually is. Thus if we can avoid visual observation the sounds of our movement may be refracted upwards in such a way as to pass over the head of the bird even at a few yards' distance, which accounts for the way in which we sometimes raise grouse almost from amongst our feet.

Similar effects are produced by temperature gradient. Sound travels more rapidly in warm air than in cool air. It follows that if the temperature decreases as we rise above the surface of the earth, the velocity of sound also decreases and we get a refraction of sound rays away from the earth as in the case of sound travelling against an adverse wind. In the case of temperature, however, the effect is the same in all directions and all rays are bent upwards as shown in fig. 25. This particular kind of temperature gradient is the normal one, and is probably most marked in the middle of a hot sunny day. The rays of the sun are absorbed by the ground, which becomes hot and heats the layers of air immediately in contact with it, the upper layers being relatively cool. Audibility is therefore poor. On the other hand, in the evening after a hot day the earth cools quickly if the sky is clear, and so cools the layers of air in contact with it. Thus temperature increases with height, the velocity of the sound also increases with height, and all rays are refracted downwards as shown in fig. 26. This

accounts for the good audibility which so often obtains in the evening.

It will be obvious from fig. 25 that the range of audibility is greatly increased if the point of observation is high, and the same result is obtained if the source is high. This will be seen from fig. 27. Rays which leave the source in a downward direction are deviated so as to become horizontal and finally move upwards again, so that if source and observer are at the same height the range is doubled as compared with that for the observer at this height and the source on the ground.

Fig. 26.—Refraction of sound rays due to a temperature gradient in which the cooler layers are below. The waves are audible to an observer at O.

No discussion of this subject would be complete without a reference to the interesting phenomenon known as the silent zone. In this case the audibility is abnormal. Observers scattered over an area lying relatively near to the source of sound may hear nothing, while observers in an area lying just beyond this silent zone may hear the sound with perfect distinctness. It is a well attested phenomenon frequently noticed in the case of shipping and during military operations. The phenomenon is hinted at by Pepys in his reference to the visit of the Dutch fleet to the Thames, and an instance is quoted by Henry[1]:

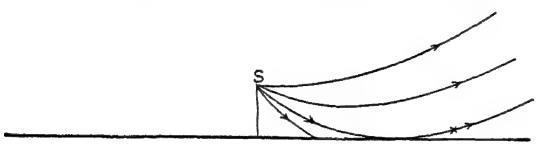


Fig. 27.—Increased range of sound waves in an unfavourable temperature gradient if the source is placed high

"General G. K. Warren informs me that at the Battle of Seven Pines in June, 1862, near Richmond, General Johnston of the confederate army was within three miles of the scene of action with a force intended to attack the flank of the northern forces, and although he listened attentively for the sound of the commencement of the engagement, the battle, which was a severe one lasting about three hours, ended without his having heard a single gun." A still more remarkable instance is given in a skirmish between a part of the 2nd Corps under General Warren and the force of the enemy. In this case the sound of the firing was heard more distinctly at General Mead's head-quarters than it was at the head-quarters of the 2nd Corps itself, although the latter

[1] Report of United States Lighthouse Board for 1874, pp. 83–7.

was about midway between the former and the point of contact. Similar phenomena are noted in the case of fog signals in the Report of the Trinity House Fog Signal Committee, 1901.

Fig. 28.—Sound Map for explosion at Silvertown, January, 1917

Dots indicate places where the sound was heard. Circles indicate places where no sound was heard. Crosses represent two places in the silent area which are on high ground and where the sound was heard. Dotted lines give a rough idea of intensity, and similar intensities in the inner and outer areas are indicated by the letters A, B, C.

Silent Area in the Silvertown Explosion.

We may take as an illustration the case of the Silvertown Ex-

plosion, which occurred at a munitions factory in January, 1917. This case has been very fully investigated by Dr. Davison, and figs. 28 and 29 are reproduced from his paper. The dots represent the reports of ob-

Fig. 29.—Sound Map showing multiple reports for explosion at Silvertown

Single reports are indicated by circles, double reports by dots, and triple and quadruple reports by crosses.

servers who heard the sound and the dotted lines are designed to give some indication of the intensity. It will be seen that the sound was audible in the normal way over an inner area which was roughly triangular, with its base running from Canterbury to Northampton,

and its apex in the neighbourhood of Ascot. Lying to the north there is a large tract of country on which small circles may be seen distributed. At these places inquiry elicited no instance of the sound being heard. Lying farther north still is a very large tract of country from which again reports of having heard the sound were received. Thus although the whole county of Cambridge and parts of adjoining counties were in the silent zone, the counties of Norfolk and Lincolnshire formed part of the area over which the sound was distinctly heard. Places within just over 20 miles of the source heard nothing, while places at about 120 miles in the same direction heard the sound distinctly.

The data collected by Dr. Davison include two other interesting factors borne out by independent evidence in other similar cases. In the outer sound area particularly many of the reports heard were multiple. In this area there are 28 records of single reports, 102 of double reports, 74 of triple reports, and 16 of quadruple reports. This is indicated in fig. 29, where single report places are denoted by small circles, double report places by dots, and triple and quadruple report places by crosses. It is fairly certain that these multiple reports are due to the sounds received by the same observer having travelled by alternative paths of different length. Another interesting observation is that in addition to the short and abrupt pressure changes which excite the sensation of sound, waves involving a comparatively slow change of pressure, and therefore inaudible, are observed. These waves may be put in evidence by the rattling of windows or the movement of blinds or curtains, and these phenomena were observed to occur at a different instant from the sound which, in the outer area, seems to have followed a long-period wave. This is rendered even more striking by a considerable volume of testimony to the fact that pheasants, so plentifully distributed over Norfolk, showed in some cases considerable agitation immediately prior to the sound being heard. The presumption is that in some way they were sensitive to the inaudible wave.

Other Explanations of the Silent Area.

Several factors may have contributed to the production of the silent zone. It seems fairly clear that it is due to refraction of the sound waves which must have been deviated upwards near the source and then deviated downwards to reach the ground again at more distant points. This would, of course, happen if the sound were travelling against the wind, and at some level reached a plane where the wind gradient was reversed. Thus if the wind velocity were to increase with height up to a certain point and then begin to diminish again, the rays would be concave upwards on leaving the source S, would then reverse their curvature at P so as to become concave downwards, and after reversing again at Q will reach the ground concave upwards (fig. 30). The same thing would happen with a reversal of temperature gradient,

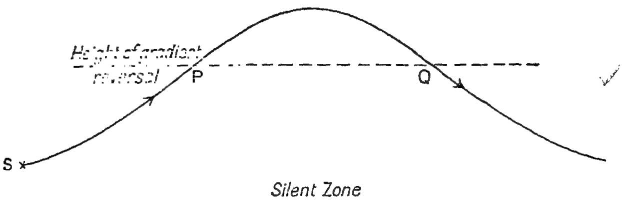


Fig. 30.—Refraction of sound rays due to reversal of wind or temperature gradient

and these two causes may co-operate. Obviously, however, if the temperature alone were effective we should get areas symmetrical with respect to the source, an inner circular area of normal audibility,

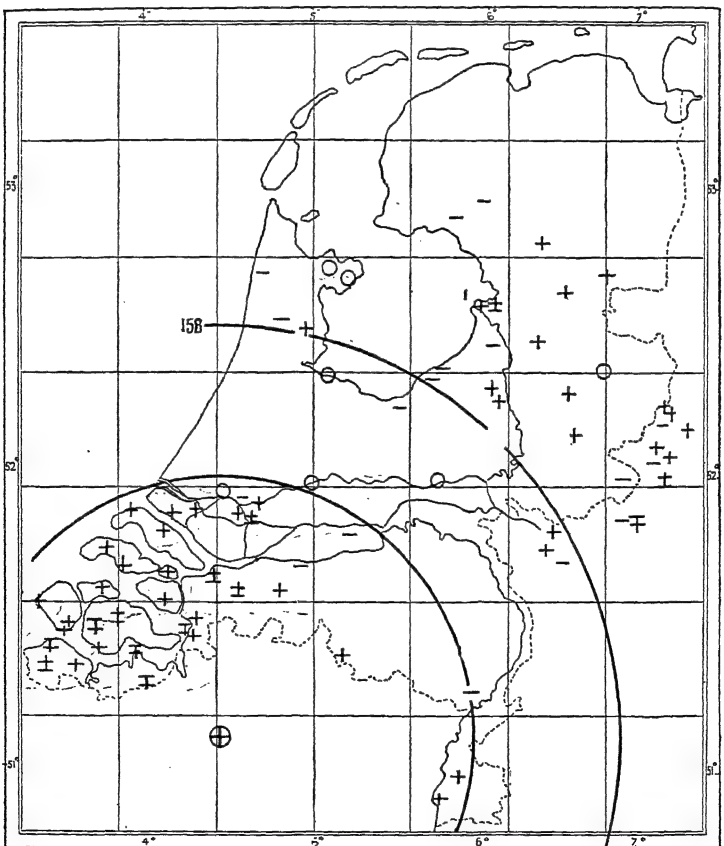


Fig. 31.—Sound Map for the Siege of Antwerp

Circles indicate negative reports; lines, single crosses, and double crosses indicate reports of increasing loudness

an annular zone of silence, and a surrounding annular zone of abnormal audibility. That this occasionally happens is maintained by van Everdingen, who has published sound maps for several engagements during the war. One of these is shown in fig. 31. It represents the observations in connexion with the siege of Antwerp, and shows an annular zone. He uses these maps, however, to support another

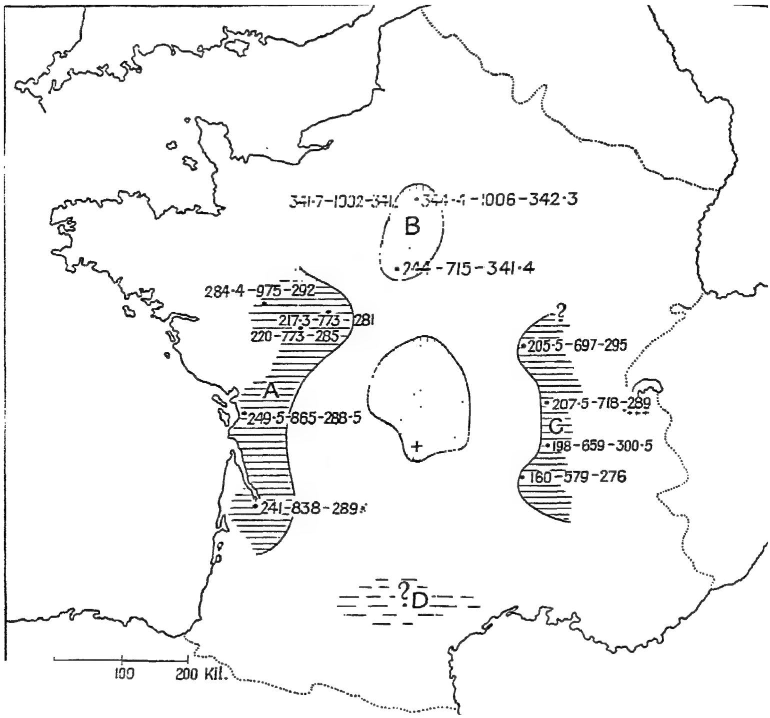


Fig. 32.—Sound Map for an explosion at La Courtine

The last figure shown for each point is the calculated velocity of sound in metres. This is normal for the area B, but abnormally low for areas A and C. Where there is no shading the sound was not audible. D represents an area for which the observations are unreliable.

explanation of the silent zone, originally proposed by von dem Borne. There is good reason to believe that the composition of the atmosphere changes in a very marked way at great heights, the proportion of hydrogen and helium increasing rapidly until they form practically the whole atmosphere. As these gases are very light and the velocity of sound in them very high in consequence, the velocity of the waves will increase with height and we shall again have refraction, waves which have been directed upwards from the source being refracted downwards and returning to the earth.

The phenomenon has been studied in connexion with volcanic explosions in Japan and also in connexion with a series of explosions of munitions dumps at La Courtine. The sound area in connexion with one of these latter explosions is shown in fig. 32, and it will be seen that there is some suggestion of a circular form. The numbers given at various points on the diagram indicate (1) the distance of the point in question from the origin of the explosion in kilometres, (2) the time interval in seconds, and (3) the velocity of the sound in metres per second. The cross in the central area indicates the source of the waves. For the area B the velocity is more or less normal (about 340 m. per second at 15° C.), but for the areas A and C it is abnormally low, and may be due to the fact that owing to the curvature of the sound path in the atmosphere the distance traversed is much longer than that measured along the surface. At present we are probably safest in assuming that all these causes may co-operate in different degrees, and we may perhaps agree in hoping that the advance of knowledge will be furthered and more sinister possibilities avoided by the extension of the policy of exploding large quantities of munitions in the interest of scientific experiment.

Transmission of Sound in Water.

The transmission of sound in water has several advantages over the transmission in air. It is attended by smaller energy losses. Also in shallow water the sound energy is contained between the surface of the water—which is a nearly perfect reflector—and the bottom, and so it only spreads in two dimensions instead of three. Before the war some experiments had been made, especially in America, and it was found that under-water sound signals were much more reliable than those in air, not only because their penetration was greater, but because the sea forms a much more homogeneous medium than the atmosphere, and the anomalous effects which we have been discussing in the case of the atmosphere are almost entirely absent in the case of the sea. The velocity of sound in water is nearly five times greater than in air, and therefore the wave-length corresponding to a given frequency is also nearly five times as great. For equal wave-lengths it is calculated that the absorption in water is one hundred times less than that in air, while for equal frequency it is about 2000 times less. One of the most interesting and useful applications of submarine signalling is the method of finding the depth of the sea by using an echo reflected from the sea-bed. If we know the time that elapses between the production of a sound at the surface of the sea and the arrival of the echo from the bottom, then knowing the velocity of sound in sea-water the depth can easily be calculated. Obviously if this method can be applied with any accuracy it represents a great saving of time and trouble as against the older method of heaving the lead.

The method of measuring the time will be understood by reference to fig. 34. Two brass discs 5 and 7 are run on the same shaft and each carries a small strip of ebonite shown in black. Bearing on the brass disc 7 are two brushes short-circuited by the disc, and completing the circuit from the mains through the transmitter. Each time the strip of ebonite comes under these brushes the circuit is broken and the spring hammer descends on to the diaphragm. Rotating on the same shaft, the other brass disc 5 short-circuits the telephone through two brushes 4, except once in each revolution when the ebonite strip 3 comes under one of the brushes. No sound will, therefore, be heard in the telephone unless the ebonite strip 3 comes under one of the brushes at the instant when the sound is produced, or at the instant when the echo reaches the hydrophone. The position of the telephone brushes can be adjusted by a milled head 1 carrying a disc 2, graduated on its edge directly with a depth scale which reads at the pointer. The shaft revolves at three revolutions per second, so that one degree displacement of the telephone brushes corresponds to rather less than $\frac{1}{1000}$ sec. or rather less than $2\frac{1}{2}$ ft. in depth. Special modifications are made for use in deep water. The apparatus can be used to obtain a continuous record of depth, and in well-charted water a ship can find its way about by comparing the soundings with the chart. It has now been fitted on over a hundred vessels, including ships of various navies, survey vessels, merchant vessels, trawlers, and submarines.

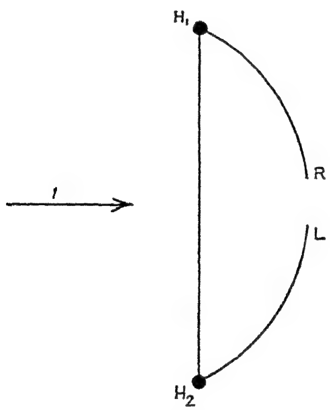


Fig. 35.—System of two hydrophones centred for a source of sound

R and L are the two ears of the observer connected by two equal paths to H_1 and H_2, the two hydrophones. The arrow gives the direction of arrival of the sound.

Binaural Method of Fixing the Direction of a Source of Sound.

Work in the American Navy has been carried out on the same problem, and special attention has been given to the matter of sounding in shallow water. One way of dealing with this is to perfect the apparatus for determining the direction of a source of sound, and this is obviously important not merely for echo-sounding but for getting the bearing of a distant submarine source of sound. The principle upon which the American work depends is that if a sound arrives simultaneously at the two ears it is impossible to place it as right or left, whereas if it arrives first at the right ear we instinctively place its source somewhere on the right-hand side, and conversely. When the sound

arrives simultaneously at the two ears it is said to be centred. We may, of course, centre the sound in two different ways. If the two hydrophones are attached at opposite ends of a rod which is movable, we

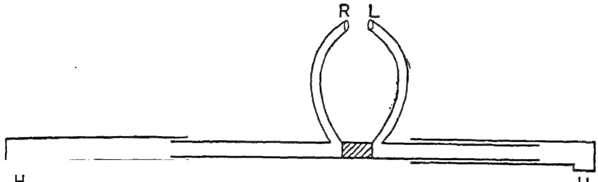


Fig. 36.—System of two hydrophones centred for a sound arriving in a direction inclined to the right

The sound arrives first at H_1, and the tube to which R, L are attached is moved towards H_2 until this earlier arrival is compensated.

can swing this rod round until the sound is centred, in which case the source of sound must be in a direction at right angles to the rod (fig. 35).

There is another less obvious method, however: keeping the position of the two hydrophones fixed, we can alter the lengths of the sound paths from the hydrophones to the ears. A simple method of effecting this is to have a tube, carrying the attachment for the two ears, sliding in two tubes carrying the hydrophones as shown in the diagram (fig. 36). The angle which the direction of the source of sound makes with the line joining the hydrophones can be calculated from the position of the middle tube when the sound is centred, and in this way the sound paths to the two ears are much more conveniently adjusted than by rotating the movable framework to which the hydrophones are attached. The most convenient form of compensator using this principle is shown in figs. 37 and 38.

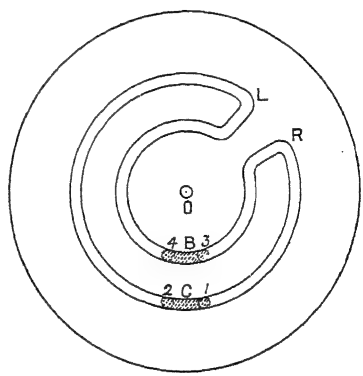


Fig. 37.—Diagram of Circular Compensator

Rotation of upper disc displaces the stops B, C and alters the relative lengths of the sound paths R and L leading to the right and left ears respectively.

The compensator is circular in form and consists of two discs, the upper one of which may be rotated with respect to the lower. Sound from one hydrophone enters at 1, passes round the channel R shown on fig. 37 to the point 3 and is then lead off to the right ear. Sound from the other hydrophone enters at 2 and is lead round the passage L to the point 4, and thence to the left ear. Rotation of the upper disc

rotates the stops B, C, and therefore adjusts the relative lengths travelled by the sound waves to the right and left ears respectively. The upper disc may carry a scale graduated so as to read directly in degrees, thus giving at once the bearing of a source of sound.

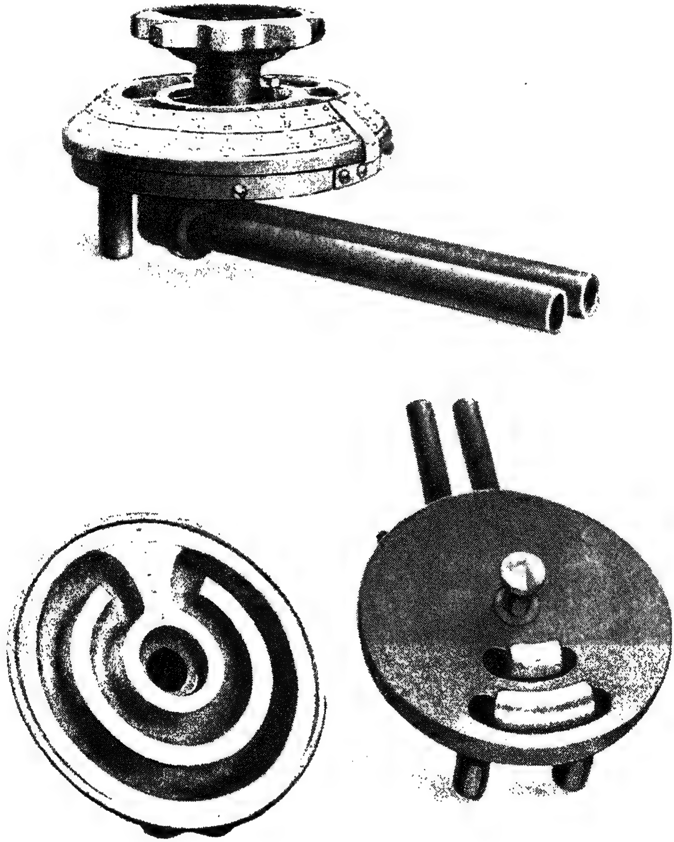
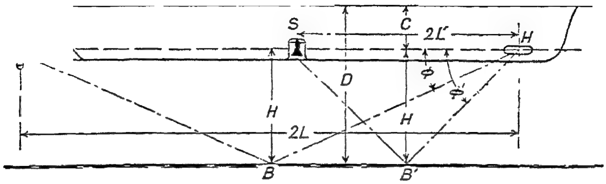


Fig. 38.—Circular Compensator, showing top cover removed

By an extension of this principle the compensator method may be applied to a set of twelve hydrophones, six connected to each ear. This has the further advantage of being highly "selective". If we think of a set of six equidistant hydrophones connected to one ear by air paths of equal lengths, then it is obvious that sounds coming from a source in a direction at right angles to a line joining the hydrophones

reaches them all simultaneously, and gives at the ear a six-fold effect. The sound from a source even slightly off this line arrives later at each successive hydrophone, and some degree of interference is produced



For deeper water $D = C + H = C + L \tan \phi$

For shallower water $D = C + H = C + L' \tan \phi'$

Fig. 39.—Sounding by Angle of Reflection Method

For deeper water the angle ϕ is made larger by using the propeller as the source of sound. For shallower water a source at the middle of the ship may be used. D is the depth of the water; C the depth of source and hydrophone below the surface; 2L the horizontal distance of source from hydrophone.

at the ear with consequent loss of loudness. The sound is centred in this case also by a form of circular compensator.

Using this method, a submarine bell has been picked up at 37 miles, and its bearing fixed to within two degrees. As applied to echo-

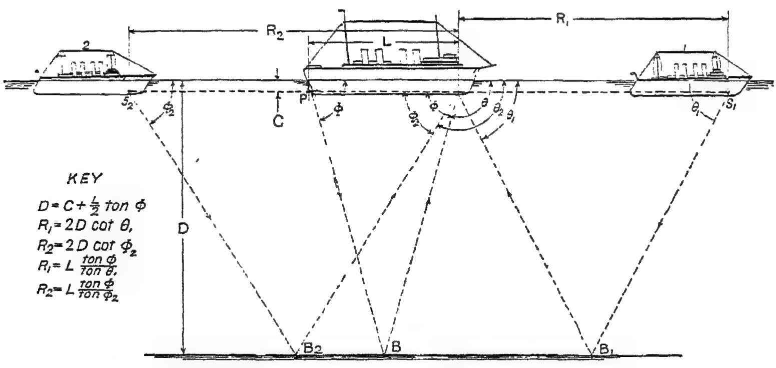


Fig. 40.—Location of other ships by echo-sounding method

D, the depth, is first obtained from the direction of the sound from the ship's own propeller reflected from the bottom. The distances of the other ships are then found in terms of D and of the angle at which the sound of their submarine bells are received by the observing ship.

sounding, the method consists in the solution of an isosceles triangle of which the base and one of the angles is known and the height is required. Fig. 39 shows the case in which a ship picks up its own propeller sound. An interesting further possibility is indicated in fig. 40,

in which having found the depth a ship is able to locate by bearing and distance any other ship in her neighbourhood.

Very remarkable results have been obtained, using this type of hydrophone, by Lieut. Hayes of the United States Navy. It has been shown to facilitate rapid navigation in shallow water, the channel being picked out entirely by use of the sounding apparatus and chart.

From the sources of sound used in the British and American methods, waves spread in every direction. There is no possibility of producing a beam of sound concentrated in a particular direction unless we can make the dimensions of the plate which acts as the source large compared with the length of the waves it emits. The frequency of the sound in the British pattern transmitter is about 1200. This corresponds to a wave-length of about 1 ft. in air or nearly 5 ft. in water. Thus the source of sound would have to be a plate o diaphragm of 20 or 30 ft. in diameter. The other way of tackling th problem would be to increase the frequency and so diminish the wave length until, with a reasonable size of source, the wave-length wa so small as to give a beam with small divergence.

Production of High-frequency Waves in Liquids.

The use of these short wave-length ultra-sonic beams was firs suggested by Lewis Richardson, just after the disaster of the *Titan* by collision with an iceberg in 1912. It was first made practical, howeve by Professor Langevin, who solved the problem of applying to wat very high frequency vibrations of sufficient amplitude. In order t

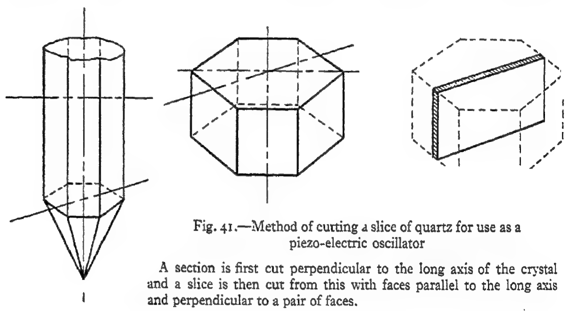


Fig. 41.—Method of cutting a slice of quartz for use as a piezo-electric oscillator

A section is first cut perpendicular to the long axis of the crystal and a slice is then cut from this with faces parallel to the long axis and perpendicular to a pair of faces.

produce the vibrations he made use of a property of quartz known as piezo-electricity. If a slice is cut from a crystal of quartz in the way indicated in fig. 41, and pressures are applied to the opposite faces, a negative electric charge will develop on one face and an equal and opposite positive charge on the other, thus producing a difference of potential between the two faces. I have here an arrangement which shows the

effect. One face of the quartz plate is connected to earth and the other to a gold-leaf electroscope. Whenever pressure is applied to the quartz the movement of the gold leaf indicates a change of potential of the insulated face (fig. 42). Now this property is reversible. Just as compression of the quartz develops a difference of potential between the faces, so the application of the same difference of potential to the faces causes the quartz to contract. The application of an alternating difference of potential will therefore produce a periodic change in the thickness of the quartz, and if one face be kept fixed the other will move to and fro owing to the changes in thickness. If this face is in contact with air, water, oil, or any other fluid, waves of compression and rarefaction, i.e. sound waves, will be generated in the fluid. In the

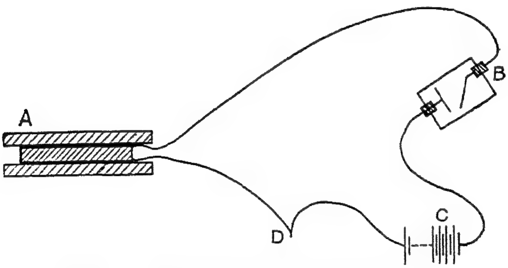


Fig. 42.—Demonstration of piezo-electric effect

A, slice of quartz placed between two metal plates between which pressure can be applied; B, Wilson tilted gold-leaf electroscope; C, battery; D, earth connexion. The upper metal plate is insulated and connected to the gold leaf. The lower metal plate is earthed as is also one terminal of the high-potential battery. The other terminal of the battery is connected to the fixed plate of the electroscope.

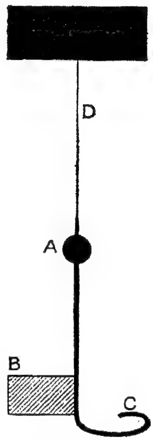
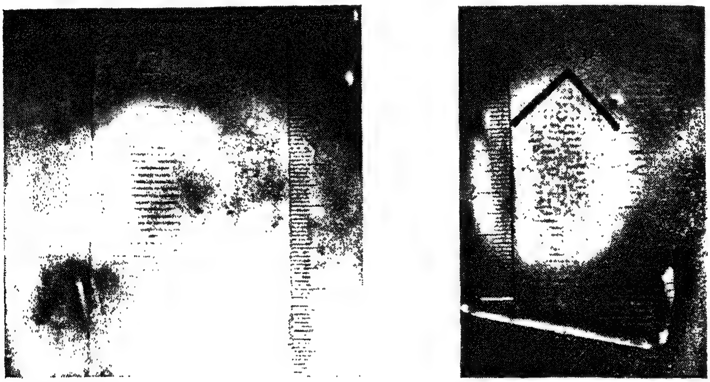


Fig. 43.—Torsion pendulum for detecting sound radiation pressure

A, mirror; B, light wooden vane; C, counterpoise; D, wire suspension.

glass tank on the table we have an insulating oil, and suspended in that with its faces vertical is a carefully tested quartz slice obtained for us by Professor Langevin. Electrodes in the form of thin metal films are cemented to its two faces, and these are connected to a valve oscillating set put together by the Marconi Company. In front of the quartz is suspended a torsion pendulum with a mirror attached, as shown in fig. 43. Since waves exert a pressure on any surface on which they fall, the radiation from the quartz striking the wooden face of the pendulum will twist the suspension, and a spot of light reflected from the mirror will move across the screen. In order to get the best results, we must remember that the quartz has a natural period of oscillation depending on its thickness, and that the amplitude of the vibration will be greatest when the oscillating potential has the natural frequency

of the quartz. For this particular quartz the natural frequency is about 500,000 cycles per second. On applying an alternating E.M.F. to the quartz we immediately see a deflection of the spot of light, and by altering the tuning of the valve circuit we see that this deflection can be made to pass through a maximum and diminish again. Leaving it at a maximum, we move the quartz round so that the beam is directed against the end of the tank. By properly adjusting the position we find the spot of light deflected in the opposite direction. A beam of waves is now being reflected from the end of the tank on to the back of the torsion pendulum, thus illustrating the reflection of the waves.



(a) (b)

Fig. 44.—Photographs of sand patterns produced on a glass plate by superposition of ultra-sonic waves and projected on a screen

a, Nodal and anti-nodal ridges produced by superposition of direct wave and waves reflected from a plane reflector. The dimensions are indicated by the millimetre scale on the right. *b*, Superposition pattern produced by waves reflected from two planes set at right angles.

In front of the quartz we now place a horizontal glass strip on which some fine sand is strewn. A beam of light is projected vertically through the bottom of the tank and through this glass plate, and the layer of sand is focused on the screen. If now a vertical glass plate be placed just beyond the end of the horizontal glass strip, the direct waves from the quartz meeting the reflected waves from the vertical plate produce a stationary wave-system, and, as we watch, the sand particles are sorted out into a series of parallel ridges running across the strip, the distance between them being a half wave-length. Their actual size shows that we are dealing with a wave-length of less than half a centimetre. If instead of the vertical glass plate we use a right-angled reflector resting on the horizontal glass strip, we get between the two halves of the reflector two sets of stationary waves and two sets of ridges running at right angles to one another, which at once

show on the screen (the photographs shown in fig. 44 are taken from the projection on the screen).

Many other interesting properties of these waves have been demonstrated by various workers. The divergence of the beam can be tested by moving the torsion pendulum across it and measuring the torsion which has to be applied to the wire in order to bring it normal to the beam in each position. In this way the relation between the wave-length, the size of the source, and the divergence of the beam, to which reference has already been made, can be verified. Also, if enough energy is communicated to the quartz, then when the direct and reflected beams are made to interfere and produce stationary waves, the changes of pressure at the nodes are so great that they show "cavitation". This means that at instants of low pressure dissolved gas escapes from solution and sheets of bubbles may be seen rising, the distance apart of the sheets giving the half wave-length of the radiation just as in the case of the sand ridges in the previous experiment.

French Echo Sounding with High-frequency Waves.

The method has been applied to the development of an ultra-sonic depth-finder by the Société de Condensation et d'Applications Mécaniques, 42 Rue de Clichy, Paris. The frequency selected is about 40,000, which gives a wave-length in water of about 3·5 cm. This

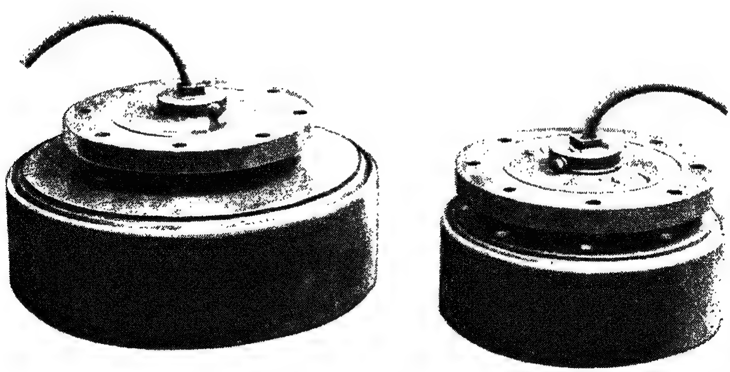


Fig. 45.—Projectors used in the French method of echo sounding for generating high-frequency wave

frequency is too great to produce an audible sound, hence the term ultra-sonic. Using a plate of diameter six to ten wave-lengths gives a pencil in which the divergence of the waves is comparatively small. There is a practical difficulty to be overcome. Plates of quartz so thick that their natural frequency is 40,000 and having a diameter of 20 to

30 cm. would be very difficult to obtain and very expensive. The difficulty of thickness is overcome by using as electrodes two steel plates cemented to the opposite faces of the quartz. These plates load the quartz and reduce its frequency, so that with a plate a few millimetres thick the necessary wave-length can be obtained. The use of these plates also enables us to substitute for the single quartz plate a mosaic of small pieces, provided these are all carefully cut and tested.

Transmitters of two different sizes are shown in fig. 45. A spark

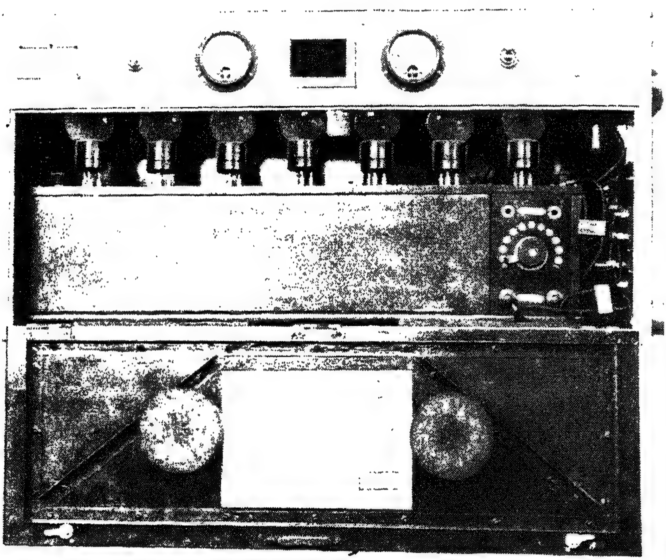


Fig. 46.—Receiver showing valve system by means of which the echo signals are amplified

is made to generate oscillations in a circuit containing a transmitter, and this circuit is tuned until its frequency is the natural frequency of the transmitter. Each spark then generates a damped train of electrical oscillations which are transformed into mechanical oscillations of the transmitter, and so into a train of compressional waves in the water which is in contact with the face. The reflected wave-train is received again on the transmitter, which piles up the energy by resonance, and the resulting oscillations of the quartz plate generate an alternating E.M.F., which is amplified by the valve system shown in fig. 46. The output from the receiver is led to an oscillograph, and the depth found in one of two ways. The oscillograph is essentially a suspended magnet system round which an electric current can be led, so as to produce a deflection measured either by a beam of

light reflected from a mirror attached to the magnet or by a pointer. By an ingenious arrangement a spot of light travels vertically down-

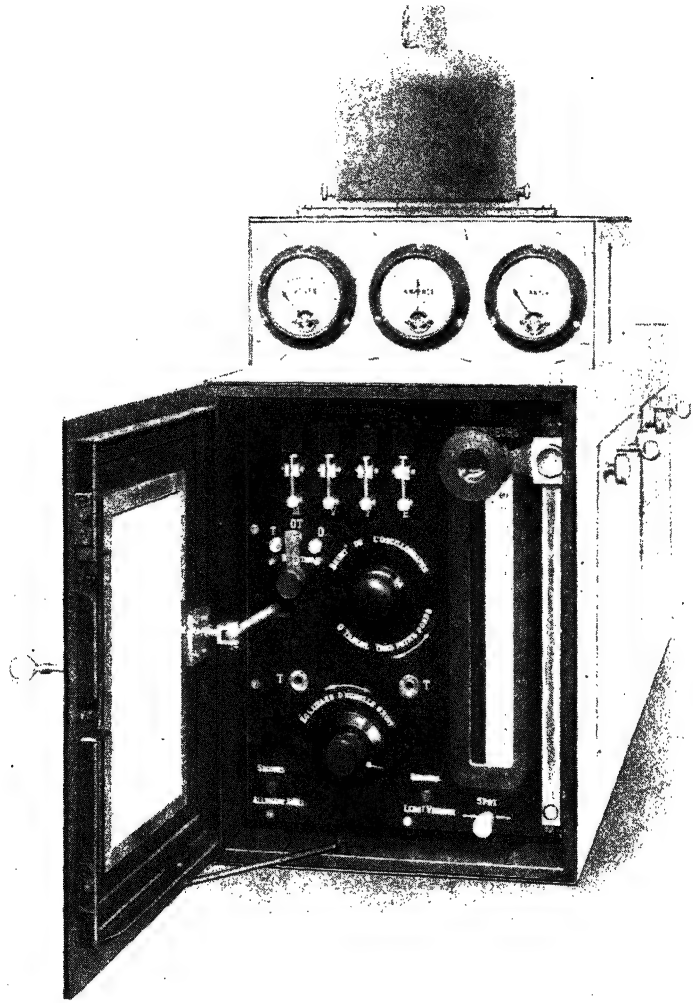


Fig. 47.—Sound analyser which controls sending and receipt of signals, with depth scale on right giving direct readings

wards with uniform speed to the left of the scale shown in the analyser (fig. 47). This spot receives a kick every time the oscillograph is put in action. This occurs at the instant of sending the signal and at the

instant of receipt of the echo. The apparatus can be adjusted so that the first kick registers the depth of the transmitter below the surface of the water, and the second kick indicates on the scale the depth of the surface from which reflection occurs. The lens shown in front of the top of the scale enables these two points to be determined with great accuracy, and the sending of the signals is performed automatically at short intervals by a motor.

Instead of this optical method of observation, a mechanical record may be obtained by attaching to the oscillograph a long needle which bears on smoked paper revolving on a drum. The drum is geared to the sparking mechanism, so that a signal is sent once in each complete revolution of the drum. If the needle is at rest it produces an unbroken line on the smoked paper, but when a signal is sent or received the needle is suddenly deflected and the kick shows on the trace. Fig. 48 shows a photograph of one of these records. The white line on top represents the surface of the water, and the distance between that and the next white line represents the depth of the transmitter below the surface. This second white line is formed by the sudden deflection of the needle due to the sounding of the signal. The wavy line lower down is made up of the kicks due to the receipt of the echo, and the distance on the record between the two kicks on any one line measures the depth of the water at the instant at which the signal was sent and received. The strong white lines represent increments of depth of 50 m.; thus, starting on the left with a depth of about 63 m., we note that this depth remains nearly constant at first, then increases to 90 at the centre of the trace, and then very rapidly to about 140, after which it gradually falls to 100.

The method of optical observation has been invented by M. Florisson, and the Société de Condensation et d'Applications Mécaniques have kindly sent over a complete set of apparatus such as has now been actually fitted on more than one hundred ships. (This apparatus was demonstrated by M. Florisson at the close of the lecture.)

Other Uses of Ultra-sonic Beams.

Another possible application of these sound beams deserves mention. They may obviously be used not only for ordinary depth determinations, but for detecting sunken obstacles, the indication being the depth of a small patch of bottom and not the average depth over a considerable area, as is the case in the ordinary echo method; but the beam may also be directed horizontally and the reflection received from a submarine or from the hull of another ship. Professor Boyle of Alberta has been carrying out experiments on the reflection from icebergs. Ice does not give a very copious reflection, but it does give enough to be detected, and the reflection from icebergs has already been registered at distances of several hundred

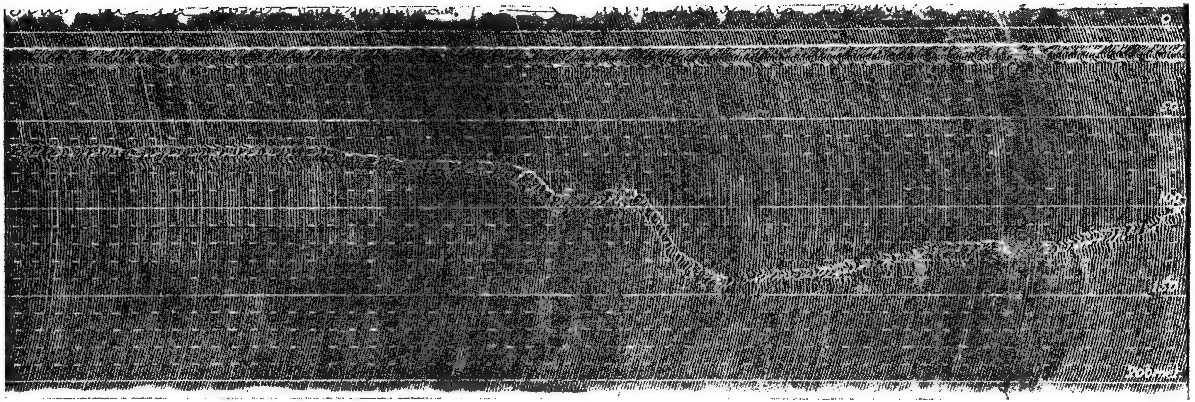


Fig. 48.—Fragment of automatic record of soundings taken by S.S. *Ile de France* in the neighbourhood of the Casquets

The depth scale in metres is shown on the extreme right

yards without using apparatus of very great power or sensitiveness.

It is possible also to telephone under water along an ultra-sonic beam by using the ultra-sonic waves as carrier, and modulating them by applying to the source an electromotive force which is varied by a microphone actuated by the voice. Experiments in this kind of telephony have been carried out successfully by Professor Langevin.

By emitting from a harbour mouth an intense ultra-sonic beam it would be possible to guide a ship. She would only have to pick up the beam and follow it, and the necessary information and instructions could be telephoned to her along the beam while she was being navigated. It is obvious, therefore, that we may look forward with confidence to increased ease and safety in navigation by the utilization of under-water sounds.

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LECTURE III

Notes and Noises

Classification of Sounds.

Sounds may be roughly classified as being either notes or noises. The division between the two classes is not sharp, and is to some extent a matter of personal judgment. Further, almost all notes have noises associated with them, and many noises have the more or less definite pitch which we are accustomed to associate with a note. If I take a piece of wood and drop it on a stone floor the resulting sound would usually be classed without hesitation as a noise, yet it has a quite definite pitch, and this fact is made abundantly clear if I drop in succession eight pieces of wood tuned to the eight notes of the octave. The wooden bars are all cut to the same length and width but vary in thickness, the thicker pieces giving the notes of higher pitch. We may treat these *claquebois* as a primitive musical instrument, and by lifting and dropping the appropriate pieces simple tunes can be played.

I have here (fig. 49) a more elaborate form of the instrument in which the bars are strung to form a sort of ladder. When struck with a hammer they give great ease of playing and produce a better quality of sound. This musical instrument is within the scope of any boy with a musical ear and a reasonable stock of patience. The xylophone is a musical instrument in which the notes are produced in this way.

Similarly the removal of the cork from a bottle gives a noise with a distinct pitch. The sound is largely due to the vibrations of the air contained in the bottle, so that as water is poured in to displace the air the pitch rises. To this fact is due the continual rising in pitch which we notice as a jug or bottle is filled at the tap. The pitch of the sound due to removing the cork is made more obvious if we take four bottles and, by blowing across the top, tune them with various quantities of water until they produce the four notes of the common chord. If we now cork them up and remove the four corks in succession, the pitch will be obvious to the most inattentive observer. In both these experiments we make the pitch obvious by directing the attention of the observer to a familiar series of notes, and this direction of the attention of the observer is a very important element in the perception and classification of sounds.

We are all accustomed to notice the scraping noise which is associated with the notes produced by an unskilled violinist. It is probable that few of us are aware of the amount of noise associated with the expert production of music. If while listening to a really skilled performer we concentrate our attention on the noise of the piano action and of the fingers of the pianist on the keys, or the scrape of the violinist, or even the breathing of the singer, we shall be surprised at the amount of noise which ordinarily escapes our notice simply because we are deliberately attending to the notes and not to the noises.

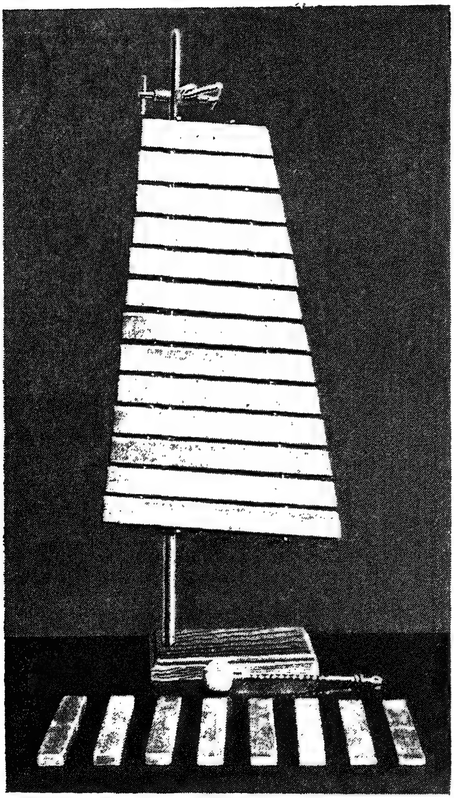


Fig. 49.—Claquebois and Xylophone

Leaving these borderland cases out of account, however, we shall find that many sounds have a smooth, regular, and pleasing character which marks them as musical, while others have a rough, irregular, unpleasant character which enables us to classify them without hesitation as noises.

Loudness.

Considering now a musical note we find that it has three definite characteristics. The first and most obvious of these is loudness. We have no difficulty in associating this with the amplitude or extent of the vibration of the source of sound. The factor to which the ear is really sensitive, however, is change of pressure at the drum of the ear, and this is associated with the amplitude of the vibration of the air in the ear passage. In some cases the vibrating source of sound may merely produce a circulation of the air in its neighbourhood without producing the compression and rarefaction which is transmitted to the ear. Thus if a string is stretched between two rigid

supports and plucked, no sound is audible. In the same way if a tuning-fork be struck and held in the hand very little sound is produced. In both these cases the motion of the air is mainly confined to the immediate neighbourhood of the vibrating body and is not propagated. Fig. 50 shows the paths of circulation of the air while a fork, the prongs of which are viewed from above, is in vibration. If now a card be placed in the position shown by the dotted line, one of these paths is

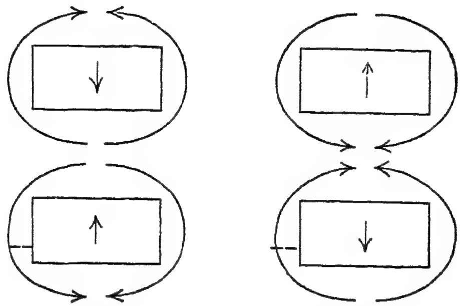


Fig. 50.—Circulation currents of air round the prongs of a vibrating tuning-fork

Insertion of card in position shown by dotted line stops part of the circulation and increases loudness.

obstructed, and the air, being unable to move round the prong so freely as it vibrates, is compressed and rarefied and the sound considerably increased. It is for this reason that in musical instruments vibrating strings always have large surfaces attached. The vibrations of the string are communicated to the sounding-board of the piano, or to the body of the violin or 'cello. The vibrations of these large surfaces make circulation impossible, and the compressional waves are produced and propagated through the air.

Pitch.

The second important characteristic of the musical note is pitch. The term is difficult to define, but we all know what is meant by a note being of high or of low pitch. Tyndall in his lectures on sound, which may still be commended to all who are interested in the subject, tells us that the physical cause of pitch was discovered by Galileo, who noticed that when a knife was passed round the edge of a piastre coin the irregularity of the milled edge caused a series of taps which, if sufficiently rapid, gave the impression of a definite pitch. The experiment can be more readily performed with a meat-saw and a post card. If the card is drawn slowly along the edge of the saw each separate tap will be heard. If it is drawn a little more rapidly a low-pitched sound is produced, while if it is drawn across very rapidly we get a high-pitched squeak. We may easily suppose that each tap produces

a vibration at the ear, and that the rapidity with which the taps succeed one another determines the pitch of the resulting sounds. The number of vibrations per second is as we have seen the frequency of the wave-motion, and we may conclude that pitch depends upon frequency.

This is further illustrated by the apparatus which I have here (fig. 51). The shaft driven by a motor has a series of eight toothed wheels, with the numbers of teeth increasing from the outside wheel to the inside wheel. The ratios of the numbers of teeth are adjusted, and when the shaft is running a strip of card passed across the series of wheels gives the eight notes of the musical scale. If, while the card is pressed on one wheel, the motor is accelerated or retarded, the pitch of the note rises or falls. This experiment also brings out a further fact—whatever the speed of the motor the eight wheels give correctly the eight notes of the musical scale, so that the pitch relations which we use in music must depend on frequency *ratios*. If, for instance, we count the number of teeth on the first and last wheels, which together give the interval of the octave, we find that one wheel has double the number of teeth carried by the other. Thus the interval of the octave is always formed by two notes, one of which has twice the frequency of the other.

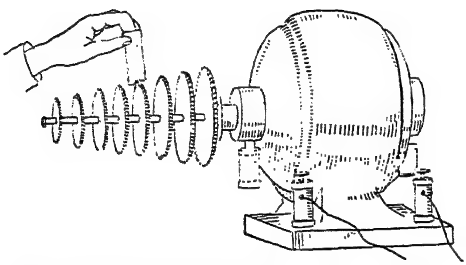


Fig. 51.—Rotating toothed wheels arranged to give the eight notes of the octave

These conclusions are confirmed by using an entirely different type of apparatus. This is the siren, which, in its simplest form, consists of a perforated disc against which is driven a blast of air from a fine nozzle. If the nozzle is placed opposite the circle of perforations, the air blast is periodically interrupted when the wheel is in motion, and the series of puffs produces a sound wave the frequency of which can be varied by varying the speed of rotation of the disc. If this disc is driven by the shaft which carries the toothed wheels of the previous experiment, it is found that the perforated disc and the toothed wheel give a note of the same pitch if the number of holes is equal to the number of teeth. With two circles of perforations, one carrying twice as many holes as the other, we get the interval of the octave whatever the speed of the motor may be.

On counting the teeth on the wheels we find the numbers 24, 27, 30, 32, 36, 40, 45, 48. These numbers enable us to find the ratio of the frequencies for the common musical intervals.

Musical Quality.

The third characteristic of the musical note is quality. This is the characteristic which enables us to distinguish two notes of the same pitch and loudness produced by different instruments, or by the same instrument in different ways. Here I have a tuning-fork (fig. 52) which may be regarded as a bar bent double and fixed at its middle point. It is mounted on a wooden box and when bowed gives a note of a certain quality. Here is a tube of the type devised by Professor Knipp (fig. 53). It consists of a small test tube with its open end presented to the closed end of a wider tube. It is held in position by three small glass studs projecting from the wider tube. It is made of pyrex glass, and when heated at the end it gives a loud tone, the pitch of which depends on the dimensions of the tube. The quality of the tone is not very different from that of the mounted

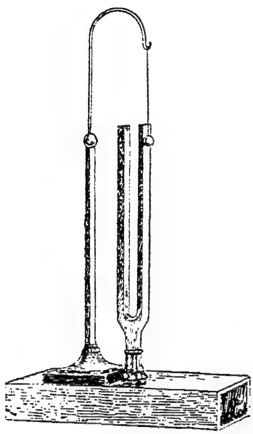


Fig. 52.—Tuning-fork and Pith Ball

Fig. 53.—Knipp Singing Tube

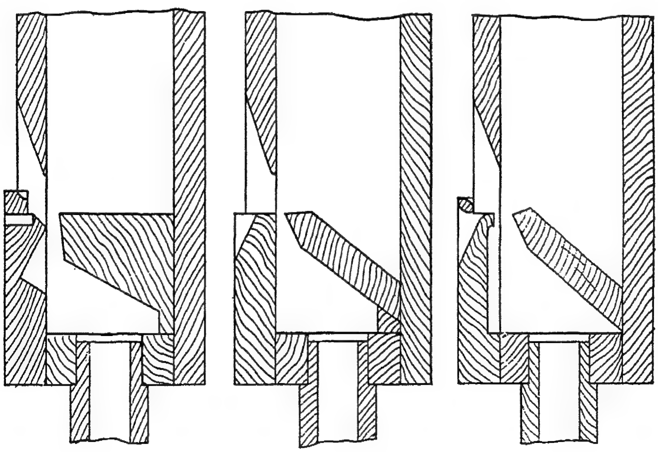
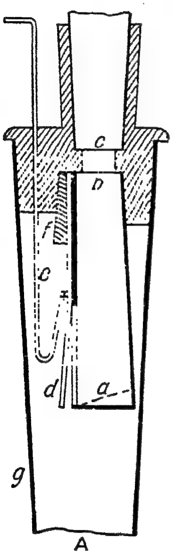


Fig. 54.—Wood Diapason Pipes of three different patterns

tuning-fork. Mounted on the wind chest we have two organ pipes. One is of the simple type known as the flue pipe (fig. 54). Like the singing tube its pitch depends on its length, the source of sound

being the vibration of the column of air enclosed in the pipe. Its quality is easily distinguished from the other two, and would probably be described as brighter or fuller. Alongside of the flue pipe is a reed pipe (fig. 55). In this pipe a blast of air is interrupted by the vibrations of a metal tongue, and the intermittent air blast which results sets the air column into vibration. Here again we have a marked difference in quality.

In order to understand these differences in quality we have to realize that most vibrating systems, strings, columns of air, &c., have several possible modes of vibration, to each of which corresponds a definite frequency and therefore definite pitch. Taking a long rubber cord fixed at one end, and moving the other end gently up and down, I can, with a little manipulation, hit the right frequency and make the cord vibrate as a whole, the centre having the greatest amplitude. Doubling the frequency of vibration of my hand I make the cord vibrate in two portions, the central point being now a node or place of minimum motion and the antinodes or places of maximum motion being one-quarter and three-fourths of the length of the string from either end (fig. 56). Making my hand vibrate faster still and watching the cord, I can hit a frequency three times as great as the first and so make the string divide itself into three equal vibrating segments separated by two nodes. With patience and skill this process can be pushed much farther, and we see that the vibrating string has a whole series of possible modes for which the frequencies are in the ratio of the natural numbers.



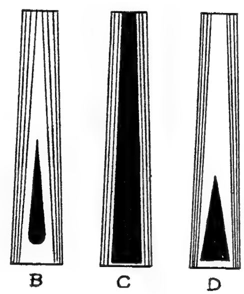


Fig. 55.—Reed Pipe

The vibrating length of the metal tongue *d* is controlled by the tuning spring *e*.

A, beating reed.
B, filled-in shallot;
C, open shallot.
D, closed.

a, head of shallot
b, tip of shallot.
c, tip of tube.
d, tongue.

e, tuning spring.
f, wedge
g, boot.

Chladni's Plate.

The same point can be brought out very beautifully by the use of Chladni's plate. This is a brass plate fixed at the centre, which can be set in vibration by using a bow. The mode of vibration is revealed by sprinkling a little sand on the plate. When the plate is vibrating

the sand gets thrown off the places of maximum motion and tends to collect along the lines of minimum motion, forming patterns from

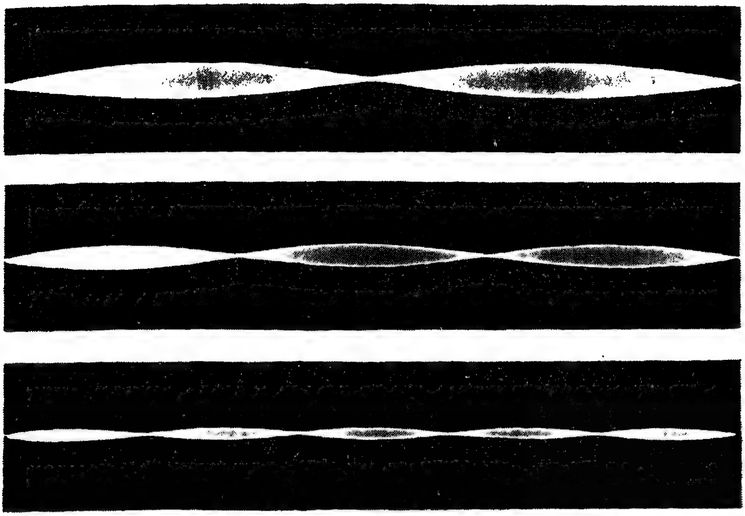


Fig. 56.—Vibrating String, showing one, two, and four nodes

which the mode of vibration can be at once deduced. The mode of vibration is controlled by the point at which the bow is applied and the point at which the finger is applied to damp the vibrations. The point of application of the bow will always be an antinode and a nodal line will reach the edge at the point touched by the finger. Symmetry will determine the rest of the pattern. Touching a corner of the square plate and bowing at the middle of one side we get the first of the patterns shown (fig. 57). Here the nodal lines are diagonals and, as always, the segments of the plate on opposite sides of a nodal line are in opposite phase. Touching

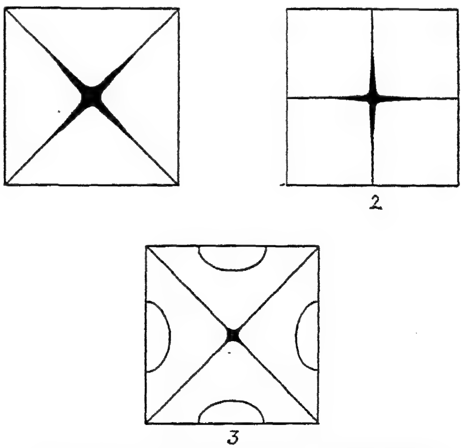


Fig. 57.—Sand patterns obtained with Chladni's plate

the plate at the mid-point of one of the sides and bowing at a corner we get the second pattern shown and a different note. Touching at the corner and another point on one side and again bowing at the centre of one side we get the third pattern shown and again a different note, this time notably higher in pitch. There is a great variety of these patterns to be got but we have only time for one more. Touching at

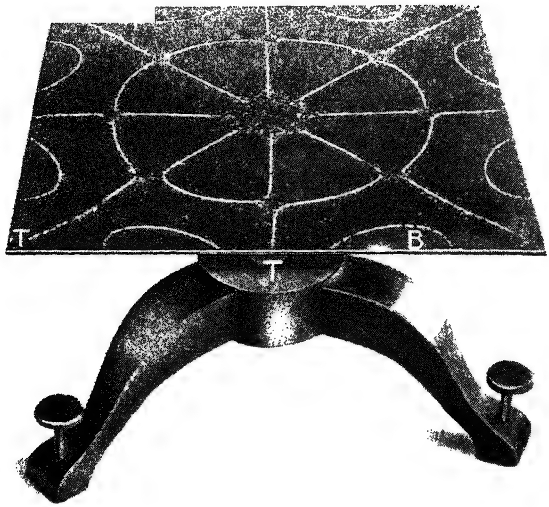


Fig. 58.—Sand pattern obtained with Chladni's plate

the points marked T and bowing at the point marked B we get a fourth pattern (fig. 58), and again a different note, notably higher than any of the others. It is not unreasonable to suppose that the peculiar clang obtained if the plate is dropped or struck is due to the fact that the complex vibration so produced is the resultant obtained by compounding simpler methods, and that the effect on the ear is due to its simultaneous perception of the corresponding notes.

Composite Nature of Musical Notes.

Returning to the case of the stretched cord whose vibrations are too slow to produce a sound, we may replace it by the stretched wire on this monochord (fig. 59), which is tuned to a frequency of 128. Placing red paper riders one-quarter and three-quarters of the length from either end and a white rider at the mid-point, I take a tuning-fork of frequency 256 and, after setting it in vibration, place its shaft on the wire where it leaves the bridge at one end. The two red riders are immediately displaced and the white rider maintains its position.

In this experiment the fork is performing the function previously performed by my hand. It is imposing on the wire a vibration of twice its natural frequency, and like the rubber cord the wire splits into two vibrating segments with a node at the centre. Arranging red riders at one-sixth, one-half, and five-sixths of the length of the wire from one end and white riders at one-third and two-thirds, and applying to the end of the wire a vibrating fork of frequency 384, the red riders are again displaced and the white riders retain their position, showing that the wire has now been thrown into three vibrating segments. Four vibrating segments are produced by a fork of frequency 512 (fig. 59). Thus the wire is capable of giving a series of tones whose frequencies are in the ratio of the natural numbers. These tones, due as a rule to

Fig. 59.—Wire vibrating in the mode of its third partial, in resonance with fork applied at one end

Two riders on wire mark the nodes.

the vibration of the system in parts, are known as partial tones. The lowest (due to the vibration of the system as a whole) is called the fundamental or first partial. The others are occasionally called overtones or harmonics, but we shall adhere to the term partial.

We shall now try to ascertain whether these tones co-exist in the note originally given by the wire. If I pluck the wire near one end you are conscious of hearing only one tone, the fundamental tone of the wire of frequency 128. If now, while the wire is singing, I touch the centre point with the corner of a handkerchief the fundamental mode of vibration (which requires a place of maximum motion at that point) is damped out and you can hear the octave sing out all over the room. The effect of the damping is not to produce a new tone, but to remove the tone on which attention was concentrated and leave the mind free to attend to the next note of the series. In the same way if the wire is damped at a point one-third of its length from one end, the twelfth (octave + fifth) with a frequency of 384, sings out unmistakably. This is the lowest tone which has a node at the point touched. The double octave and higher tones can easily be demonstrated in the same way.

The same effect can be demonstrated on the piano by using the

principle of resonance. Depress the key corresponding to middle C and so free the corresponding strings; now sound the C an octave below loudly, and when that key is released middle C will be heard sounding fairly strongly. The strings corresponding to middle C have been set in vibration in response to the octave partial of the lower C. It can easily be demonstrated that this happens only with the C an octave below and not with the adjacent keys. In the same way if the G above middle C or the C above that be depressed, it can be made to respond by sounding the C an octave below middle C. These responses can only occur if the corresponding tones occur as constituents of the note which is sounded.

Analysis of Musical Notes by Ear.

Returning to the monochord, we find that we do not require to damp the wire at all in order to hear these partial tones. If I sound the fork of frequency 256 as a guide to what to look for and pluck the wire near one end, then with a little effort and attention you will hear the octave while the fundamental is still sounding. The presence of the third partial is sometimes even more obvious. This power of analysis is one of the most striking properties of the human ear. It is a power which in some respects we habitually exercise and even in its normal use it is sufficiently wonderful. The pressure in the ear passage undergoes periodic variations, which are the result of combining the pressure changes due to all the sounds being produced at any given moment, while we are able to sort out the constituents in such a way as to listen at will to any one source. In a room where general conversation is in progress we can attend to any one of several speakers. During the performance of a quartet we can follow at will any one of the parts, while at an orchestral concert we can isolate the first violins, 'cellos, wood-wind, or tympani from the general mass of sound. In these cases we are, no doubt, assisted to some extent by the fact that the sources are differently placed. We do not ordinarily carry the process of analysis farther than this—perhaps because it serves no useful purpose—but with a little training and effort we can, without difficulty, recognize the constituent simple tones in any single musical note, and this represents a power of analysis still more remarkable.

According to Helmholtz, all differences in quality are due to differences in the number and relative intensities of the partial tones present in a musical note. If I pluck the wire first at the centre and then near one end I produce two notes of the same pitch. I can arrange to have them of equal loudness, but there is a marked difference in quality, which is explained at once on the view I have been indicating. If we pluck at the centre we make it impossible for the wire to sound any partial tone which requires the centre as a node. This cuts out

every second member of the series of partials and gives us the dull and nasal quality which you hear.

This variation in the quality of tone with the point of attack on the string is recognized and used by the violinist, who, by varying the distance of the point of attack from the bridge, can produce a noticeable difference in the quality of the sound.

Beats.

Let us now turn to consider the phenomenon of *beats*. If two sources of sound are exactly in unison, then when set in vibration simultaneously they produce a sound of uniform loudness. If, however, they differ slightly in pitch the resulting sound swells and lulls, and we have the phenomenon known as beating. At the instant of maximum loudness the two sources are in phase, and compressions and rarefactions from both reach the ear simultaneously. One of them, however, is vibrating a little faster than the other and so gradually gains. Presently it will be half a vibration ahead, so that rarefactions from it will reach the ear simultaneously with compressions from the slower source and vice versa. Thus the changes of pressure at the ear will be a minimum and the sound very weak. If the two sources are producing sounds of equal loudness, then at the instant when they are in opposition there will be no resultant sound at all. It is clear that the interval between two beats is the time taken by one source to gain a complete vibration on the other, so that the number of beats per second will be the difference in frequency of the sources. Here we have two tuning-forks in unison. I load the prongs of one of them with wax. The ear cannot appreciate the difference in pitch, but we now get a slow beating; adding more wax and repeating the experiment the beating becomes more rapid. Here we have two organ pipes of nearly equal pitch. When sounded together we get powerful beating, which can be modified by shading the end of the sharper pipe. This lowers its pitch and slows the beating. The pipe is correctly tuned when the beating disappears, and this provides us with an extremely accurate method of tuning. Slow beating is not unpleasant, in fact it makes a certain æsthetic appeal, and the stop known as the Voix Céleste on the organ consists of pairs of mistuned pipes producing this beating effect. On the other hand, as the rapidity of beating increases the sensation becomes distinctly disagreeable and passes into a roughness known as dissonance, which is extremely unpleasant. We shall return to this int later.

Combination Tones.

Before we can realize the full complexity of the effect produced by sounding a chord on a musical instrument, we must take into account still another type of tone known as the combination tone.

When two sources of sound are developing loud notes, a third note is easily heard whose frequency is the difference in frequency of the two "primes". These tones were first discovered by the organist de Sorge, and later by the violinist Tartini. The instrument which gives the most striking demonstration of these tones is the simple little instrument I hold in my hand, the police or referee's whistle (fig. 60). It consists essentially of two barrels side by side, each of which gives a high-pitched note, the difference in pitch being about a couple of tones. When the whistle is strongly blown, the most notable feature of the noise is not the constituent high-pitched tones but a loud low-pitched buzz which is the combination tone. Here I have what is in effect an adjustable referee's whistle. The length of the barrel of one pipe can be altered. If this adjustable pipe is the lower in pitch, then if its pitch is still further lowered the difference in frequency is increased and the frequency and therefore the pitch of the combination tone is raised. This makes the combination tone easier to pick out and you will notice its variation in pitch as I adjust the whistle. This particular type of combination tone is known as the difference tone or differential tone, because its frequency is the difference in frequency of the two developing tones. There is another combination tone known as the summational tone, whose frequency is the sum of the frequencies of the two developing tones, but this is much harder to hear and is probably of little musical importance. It has been shown by Helmholtz that the existence of these tones follows at once from a study of the mechanics of vibrations. When two simple tones are strongly sounded and act on the same vibrating system, the amplitudes developed may be so large that when the system is displaced the restoring force is no longer proportional to the amount of the displacement. This is assumed as the basis of the principle of superposition. If it ceases to be true other tones will be introduced and these will have the frequencies required for the observed combination tones. On the other hand, although combination tones are most obvious with intense sources of sound, they can be observed with comparatively feeble sources.

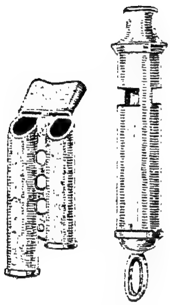


Fig. 60.—Referee's Whistles, showing the two barrels which together produce the combination tone

This has been explained by Waetzmann, who has shown that if the response of a vibrating system is not symmetrical, i.e. if a given force displaces it more in one direction than the same force when acting in the opposite direction, then it will give rise to combination tones for comparatively feeble sources. This we know to be the case for the drum of the ear, which, as we shall see, is a membrane loaded

on one side. In this case the combination tones are produced in the ear. This explains the fact that in some cases, i.e. with intense sources, the combination tones can be reinforced by appropriate resonators held to the ear, and can be detected objectively altogether independently of the ear, while in other cases a resonator held to the ear produces no effect, and although the combination tones can be heard they cannot be objectively demonstrated. In these cases, i.e. with weak sources, they are subjective in the sense that they are produced in the mechanism of the ear. This brings home a very important fact which we shall meet again, namely, that the sound heard may not correspond to the pressure waves produced by the source, or that quality may be affected by the action of the ear itself.

Thus we see that when the three notes forming, say, the major triad are sounded simultaneously on a musical instrument, each carries with it a series of partial tones of which the first five or six are easily recognizable by ear, and each of these partial tones can produce with any other partial tone combination tones of the kind we have just been discussing. It is probable that all these contribute to the musical effect produced on the ear.

Consonance and Dissonance.

We are now in a position to understand the physical difference between consonance and dissonance. Two notes which do not greatly differ in pitch act together so as to produce beats. These beats cause a roughness to which may be attributed at once the unpleasant dissonance of the semitone interval and the tone. We shall see later, however, that it is improbable that beats can be produced between two notes separated by a wide interval. Now the interval of the major seventh is one of the most unpleasantly dissonant intervals which we have, yet on the view to be developed later the interval is too great for beats. The dissonance is at once explained, however, when we remember that the second partial of the lower note, i.e. the octave, is only a semitone from the higher note, and the dissonance can be explained as due to rapid beating between these two.

If we assume then that the notes used in music carry with them a harmonic series—and this, as we have seen, is almost universally true—then in order to estimate the dissonance of a combination of notes we have only to look for the pairs of harmonics which may produce beating, and it will be sufficient to consider those which are a tone or less apart.

As pitch relations depend on frequency ratios, it follows that in order to add two intervals we must multiply the corresponding ratios, and to subtract two intervals we must divide the corresponding ratios. This is unnecessarily confusing, and has the further disadvantage that it is difficult to estimate the relative size of two intervals by a com-

parison of the ratios. Thus, if we take again the series of numbers 24, 27, 30, 32, 36, 40, 45, 48, which we have seen to represent the ratios of the frequencies of the notes of the scale, we find that the first interval, the tone, is given by the ratio 27/24 or 9/8, while the last step is given by 48/45 or 16/15 and is a semitone. It is not easy to see that the last ratio squared is nearly equal to the first, so that as a pitch interval it is approximately half the first. The whole question of intervals becomes enormously simplified when we remember that to multiply two numbers together we add their logarithms, while to divide one number by another we substract their logarithms. If therefore we represent pitch intervals by the logarithms of the ratios we shall be able to add, subtract, and compare at sight. The octave is represented by the ratio 2, the logarithm of which to the base 10 is ·3010. In order to get convenient numbers this may be multiplied by 1000, and we can say that the octave contains 301 unit intervals. This unit has been widely adopted and is known as the savart, after a distinguished French acoustician. To get the first interval on our scale we subtract log 24 from log 27 and multiply by 1000.

log 27	1·4314
log 24	1·3802
	·0512

The tone, therefore, contains 1000 × ·0512 savarts or 51·2.

Dealing now with the semitone which finishes the series, we have:

log 48	·6812
log 45	·6532
	·0280

This gives us 28 savarts or very approximately half the preceding interval.

Using this method of measuring intervals, we can very easily discover the causes of dissonance in the various musical intervals. On this strip of wood, painted white, there are marked off with black strips distances from the zero end proportional to the logarithms of 2, 3, 4, 5, and 6. These distances, therefore, represent the musical intervals between the note and its harmonic partials. Taking another strip marked off in exactly the same way and arranging them edge to edge, we get a representation of the unison; all the partials of one note coincide with the partials of the other and there is no dissonance (fig. 61). Sliding one strip past the other till the division marked 1 on it coincides with the division marked 2 on the other, we have the state of affairs when an octave is being sounded (fig. 62). In this case

alternate partials of the one coincide with partials of the other, and we see the physical reason for the close relationship of the octave, which is, no doubt, the cause of its universal occurrence in the scales of all nations and races. We see that if the lower note be first played the upper note adds nothing to it, but only reinforces some elements already present. There is no beating and no dissonance. The intervals of the fifth, fourth, sixth, and major and minor thirds are all shown in fig. 63. In the case of the major third we notice that the fourth

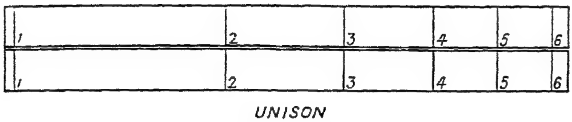


Fig. 61.—Two scales set out to represent the first six partial tones for each of two notes
The scales are placed edge to edge in the position for representing unison

partial of the higher tone coincides with the fifth of the lower, but that the third of the higher tone is a tone from the fourth of the lower note, and the fifth of the higher note a semitone from the sixth of the lower tone. There is thus considerable dissonance due to the beating of these pairs of partials. In fig. 63 the length representing a tone is shown on the diagram, and the pairs of partials forming dissonant intervals of a tone or less are shown by arrows. In general, the lower the order of the dissonant partials the rougher the interval, although this has to be qualified in the case where higher partials are relatively

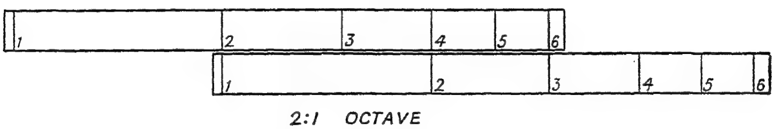


Fig. 62.—Two scales set to represent the relative distribution of partial tones for two notes sounding the octave

stronger than the lower ones. In order that the comparison may be a fair one, however, we must consider intervals in the same range of pitch. Dissonance is, as a rule, less marked in the bass register than in the neighbourhood of middle C. With this qualification we can arrange the whole series of musical intervals in order of roughness, and our order will be found to correspond to that in which the musician places them on purely æsthetic grounds. This is as far as physics will allow us to go. At what stage in this series the musician should stop is a question to be decided on æsthetic grounds, and the present tendency is to go farther and farther in the direction of dissonance. Intervals which at one time were regarded as outside the pale are now moderately

respectable, and the process does not yet seem to have worked itself out. There is some indication, however, that a reaction in favour of greater smoothness and beauty is beginning to gather momentum.

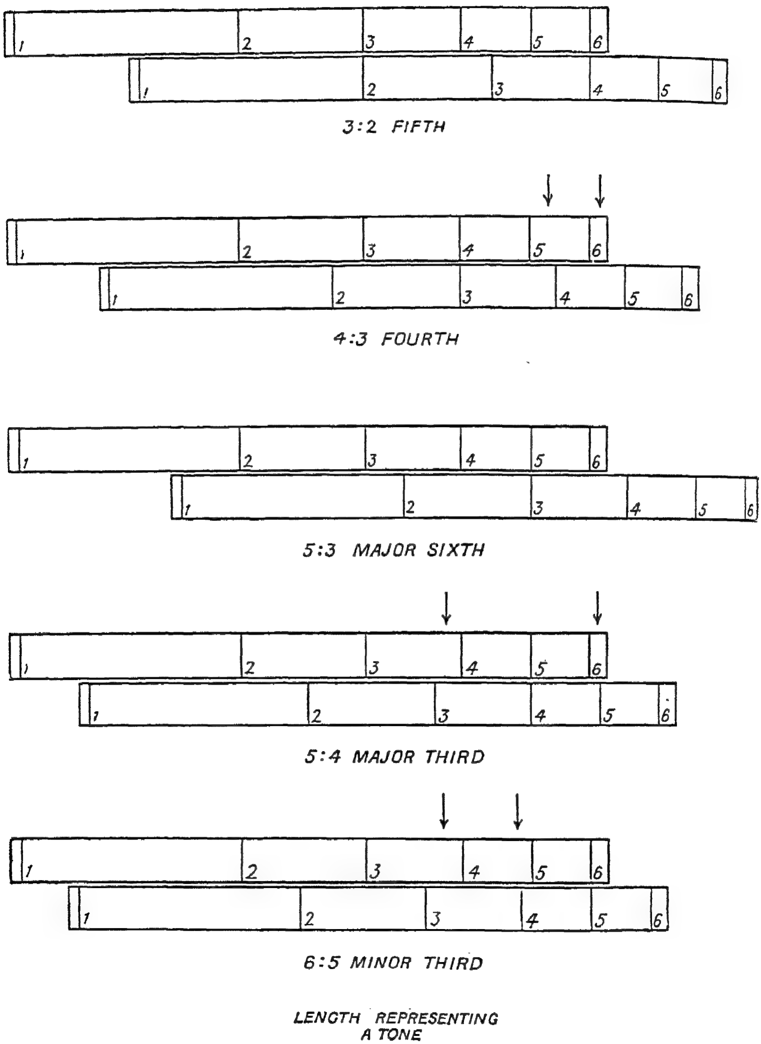


Fig. 63.—Consonant Intervals

In each case the upper scale represents the lower note of the interval. The arrows mark pairs of partials separated by the interval of a tone or less.

Selection of a Scale.

The last point with which I wish to deal is the ground on which we have selected the series of notes known as the diatonic scale, which is the basis of all our music. There are two possibilities. These particular notes may have been chosen because of the simple relationships in which they stand to one another. Thus starting with one note as the key note, it is most simply related to the note whose fundamental coincides with the second partial of the key note. This gives us the eighth note or octave. The next simplest relationship is that of the tone whose third partial coincides with the second partial of the key note. This is the fifth note of the major scale. The note whose third partial coincides with the fourth partial of the key note gives us the fourth note of the scale, while the third and sixth notes of the scale are such that the fourth partial of one and the third partial of the other coincides with the fifth partial of the key note. We now have the first, third, fourth, fifth, sixth, and eighth notes of the major scale. To pursue this process any farther would be to get into the region of the fanciful. We still have two large gaps in the scale, but the relationship between the notes required to fill them and the key note would correspond to a coincidence of partial tones which the ear could hardly be expected to appreciate. It seems reasonable therefore to select for these gaps two notes which, although not closely related to the key note itself, are closely related to the note which in turn is the nearest relative to the key note. This is the fifth of the scale or dominant. The note a fourth below this gives the second of the scale, while that a major third above it gives the seventh and the major scale is complete.

Exactly the same result would have been attained if, instead of considering the melodic relation between the notes, we had decided to choose for our scale a series of notes which gave the widest possibilities of consonances. The third, fourth, fifth, and sixth would all form consonances with the key note or tonic, while the second and seventh form consonances with the dominant. The scale was, of course, very largely developed before harmony was introduced, but it has been suggested that much early music being string music the persistance of a note on one string until the next string was sounded may have made harmony an unconscious factor in the development. The octave is a natural interval which occurs in all scales, but the number of intervals into which the octave is subdivided varies in different nations, and there is no physical basis on which we can decide the best size for the unit interval. Assuming, however, that we wish to insert six notes in the interval of the octave, we see that there is very good physical justification for the particular selection just indicated. This is our true scale, and the intervals between the notes are shown in the following table. (The first column gives the note;

the second gives the interval from the key note defined as a ratio of frequencies; the third gives the interval from the key note in savarts, found, as before, by taking the logarithm of the ratio and multiplying by 1000; the fourth column gives the interval between the successive notes of the scale measured also in savarts.)

Note.	Interval from Tonic.		Interval between Successive Notes in Savarts.
	Ratio.	Savarts.	
C	1	0	
			51·1
D	9/8	51·1	
			45·8
E	5/4	96·9	
			28·1
F	4/3	125·0	
			51·1
G	3/2	176·1	
			45·8
A	5/3	221·9	
			51·1
B	15/8	273·0	
			28·0
c	2	301·0	

It will be seen that the intervals between successive notes are of three different sizes, the large tone (51·1), the lesser tone (45·8), and the semitone (28). So long as we confine our music to one key these eight notes of the octave are sufficient, and we have a scale which corresponds roughly to the white notes of the piano, but only roughly, for a reason which will immediately be apparent. Music performed always in one key soon becomes monotonous, and the composer demands the right to change his key or modulate. Let us suppose that he performs the common modulation into the key of the dominant or fifth. We have now to find the true scale of G.

Starting with G (176·1), we have to add successively the intervals given in the third column of the preceding table in order to obtain the successive notes of the new scale.

G	176·1		
A	176·1 + 51·1	=	227·2
B	176·1 + 96·9	=	273·0
C	176·1 + 125	=	301·1
d	176·1 + 176·1	=	352·2
e	176·1 + 221·9	=	398·0
f	176·1 + 273·0	=	449·1

Taking the last three notes down an octave by subtracting 301·0 from each, we can compare the two scales thus:

	Scale of C Major.	Scale of G Major.
C	0	0
D	51·1	51·2
E	96·9	97·0
F	125·0	148·1
G	176·1	176·1
A	221·9	227·2
B	273·0	273·0
c	301·0	301·1

The Tempered Scale.

The table shows the notes required for the new scale, and we find that while six of the eight notes in the original octave are exactly correct for the new scale, one, the A, is a little out, while another, the F, is badly out. To get correct intonation and give freedom to modulate into this new key and back again we therefore require ten notes to the octave. Each new key to which we demand access lands us into the necessity of adding two more notes. Clearly if we are to have complete freedom of modulation into any key we choose, the number of notes to the octave will be so great that music would be very difficult to write or to read, and the construction and use of keyed instruments like the piano and the organ would become almost impossible. This is a matter on which physics has nothing to say. It is the musician who must decide whether modulation or accuracy of intonation is the more important from the artistic point of view. The musician has plumped for modulation, and we have, therefore, been forced to adopt a scale in which a form of compromise is applied. Notes which are nearly the same like the A above are treated as identical, while in the case of the F a new note called F sharp is introduced. In this way it is found possible to do with twelve notes, and the octave is divided into twelve equal intervals called tempered semitones. This process of tempering the scale—or as Professor Horace Lamb has called it, " tampering with the scale "—cannot be described as entirely satisfactory.

Here I have six forks arranged in two sets of three forks each; in the first the forks are tuned to the first, third, and fifth notes of the major scale and give the major triad in true intonation. When these forks are bowed and made to sound simultaneously you notice how beautifully smooth the chord sounds. The second set of forks is tuned in the tempered scale to give the same chord, and you cannot help noticing a palpable roughness in comparison.

The interval of the tempered semitone will be $\frac{301}{12} = 25{\cdot}1$ (approx.), while the tempered tone will be $2 \times 25{\cdot}1 = 50{\cdot}2$ (approx.).

Another used in which the
octave amounts,
to mult less than
4. The process
are easier to handle.

	True Scale of C Major.		Tempered Scale.	
	Savarts.	Cents.	Savarts.	Cents.
C	0	0	0	0
D	51·1	204	50·2	200
E	96·9	386	100·4	400
F	125·0	498	125·5	500
G	176·1	702	175·6	700
A	221·9	884	225·8	900
B	273·0	1088	276·0	1100
c	301·0	1200	301·0	1200

The two scales are set out in the above table in both units, and it will be noticed that the second, fourth, fifth, and eighth are very nearl correct, but the third, sixth, and seventh are badly out. The error i the case of the third is about one-sixth of a semitone, a differenc which is easily perceptible even in melody to a trained ear, and roughen the interval in harmony so that even an untrained ear can detect th difference.

LECTURE IV

How Sounds are Analysed

Simple Harmonic Curves.

We have already seen that a simple tone is associated with what is known as a simple harmonic vibration. This type of vibration is approximately that of a simple pendulum bob when the amplitude of its motion is small. It is approximately that also of the prong of a tuning-fork. In order to study to-and-fro vibrations we may record them on a surface moving at right angles to the direction of vibration. Here I have a heavy tuning-fork with a metal pointer attached to one prong. The vibration of the prong is vertical, and the flexible metal pointer bears on a glass plate which has been smoked. If now the tuning-fork is set in vibration and I draw the plate horizontally past

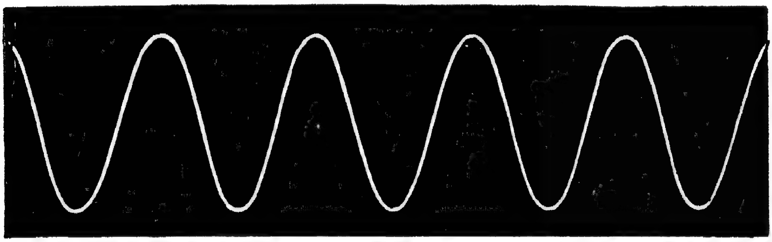


Fig. 64.—Trace produced on smoked paper by the vibrating prong of a tuning-fork drawn steadily across it

it, I get the kind of trace shown in fig. 64, a curve known to mathematicians as a sine curve. This is really a displacement curve for the vibrating fork, which shows us the successive positions of the prong of the fork at successive instants of time, and a curve of this kind gives us extremely valuable information about the motion for which it is drawn.

This particular form of displacement curve, the simple harmonic or sine curve, can be varied only in two ways. If I had used a tuning-fork of twice the frequency and drawn it past the plate at the same speed, I should have obtained a curve containing twice as many waves in the same length. On the other hand, I might have driven the tuning-fork in such a way as to give a greater amplitude, in which case the number of waves would have remained the same but the height of the

crest above the mean line would have been increased. Simple harmonic curves differ among themselves only in these two ways—wave-length (corresponding to frequency) and amplitude. We shall see later that the type of vibration which these curves represent is associated with pure tones, and pure tones therefore differ among themselves only in respect of frequency or pitch and amplitude or loudness. They show no difference in quality, a result which we should expect from the explanation of quality given in the preceding chapter.

Composition of Simple Harmonic Curves.

Now, according to the principle of superposition, if two pure tones are being simultaneously produced, the resulting displacement of the air at any point at any instant is as a rule simply the algebraic sum of

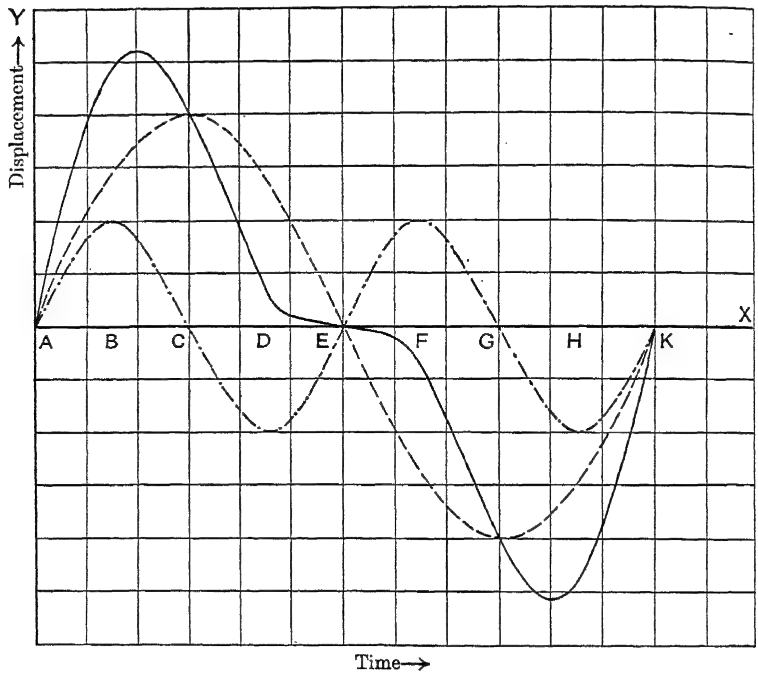


Fig. 65.—Composition of Displacement Curves

The dotted curves represent displacements due to a note and its octave. The continuous curve represents the resultant displacements when the two are compounded.

the displacements which the two simple tones would separately produce. If therefore we can draw on the same diagram the displacement curves showing the displacement of the air at a given point due to each of two separate simple tones, then by summing the ordinates for

each point on the axis we get the resultant displacement due to the two tones combined. As the motion of the air is longitudinal, i.e. to and fro in the direction of propagation, it is usual to adopt the convention that forward displacements are represented by upward drawn ordinates and backward displacements by downward drawn ordinates.

Let fig. 65 represent the displacement curves due to two separate tones in one of their possible relative positions. One curve crosses the axis twice as frequently as the other, and therefore represents the tone an octave above. Also the lower note has the larger amplitude. In order to get the displacement curve representing the combined effect we have to add the ordinates. Some points can be determined by inspection. At the instants represented by A, E, and K there is no displacement due to either tone. The resultant curve therefore crosses the axis at these points. At C and G there is no displacement due to the tone of higher pitch, and the resultant displacement is therefore that of the lower tone alone. Between A and C and between G and K the displacements due to the two tones are in the same direction and must be added, but between C and G they are in opposite directions and must therefore be subtracted. This process of compounding vibrations or building up complex vibrations from simple ones can obviously be carried out not merely with two but with any number.

Analysis of Simple Harmonic Curves.

The mathematician Fourier enunciated in 1822 a theorem which for our purpose may be stated as follows: Any type of vibration however complicated can be analysed into a series of simple harmonic vibrations whose frequencies are in the ratio 1 : 2 : 3 : 4, &c., the frequency of the motion to be analysed being 1. At first sight this is a very remarkable theorem. It seems incredible that a vibration represented by a straight-line graph as in fig. 66 can be built up out of or analysed into a series of the smooth sine curves of the type we have been discussing; yet such is the case and the result of the analysis is perfectly definite. Given the graph corresponding to the complicated vibration, the constituent simple harmonic vibrations may be determined, together with the amplitude of each and the relative positions along the axis. Corresponding to

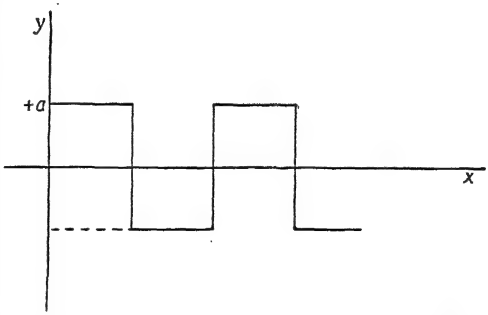
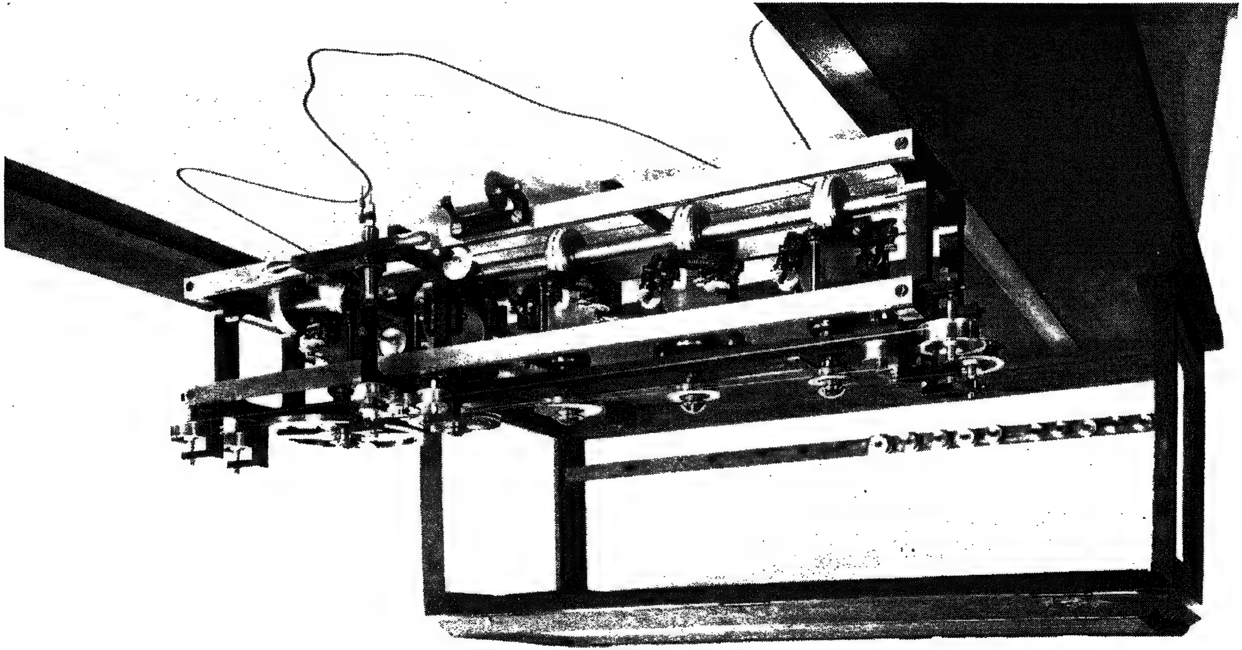


Fig. 66.—Straight-line graph which may be built up by compounding a suitable series of simple harmonic curves



this theorem we have what is known as Ohm's Law, which states that the ear perceives as a simple tone only a simple harmonic vibration, and that with any other type of vibration it can distinguish a series of separate simple tones. Thus the ear may act as a harmonic analyser, perceiving separately the vibrations corresponding to the constituent partial tones.

Now in order that we may pursue further our researches into musical quality, it is very desirable to have some method of analysing musical notes. A considerable number of instruments have been devised which perform this task of harmonic analysis mechanically. One of the earliest was due to Lord Kelvin, and was used in work on tide prediction. Another type due to Dr. Henrici (fig. 67) has been loaned by the authorities of the Science Museum, South Kensington, and can be seen on the table. The graph corresponding to a vibration is placed on the base of the instrument and a pointer made to trace out the graph. The relative amplitudes of the first few constituent vibrations can then be read off. Obviously then if we can produce a graph corresponding to the air vibration associated with a particular sound, and can then analyse the graph with some form of harmonic analyser, we shall be in a position to ascertain the relationship between the various partial tones which give to the musical note its peculiar quality.

Methods of obtaining Sound "Autographs".

One of the earliest attempts to obtain a sound autograph was made by using an instrument known as Scott's phonautograph (fig. 68).

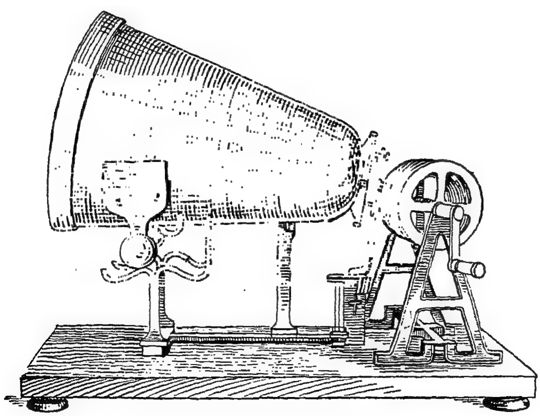


Fig. 68.—Scott's Phonautograph

It consisted essentially of a horn which acted as receiver and concentrated the sound waves on a flexible diaphragm. To this flexible

diaphragm was attached a pointer which traced on a smoked surface. In this way a curve was obtained which more or less reproduced the to-and-fro motion of the air in contact with the diaphragm. Later the

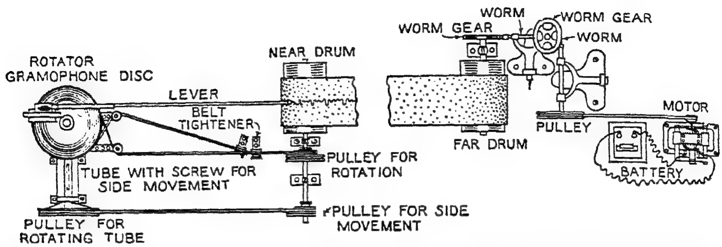


Fig. 69.—Apparatus used by E. W. Scripture to obtain a magnified graphical trace of the vibrations recorded on a gramophone disc

One end of the lever follows the groove of the record, the other produces a trace on a smoked drum.

phonograph was used for the same purpose. The early phonograph produced on a rotating cylinder of wax a furrow of varying depth, the tracing point moving in to or out from the wax with the motion of the diaphragm on which the sound impinged. One end of a long light

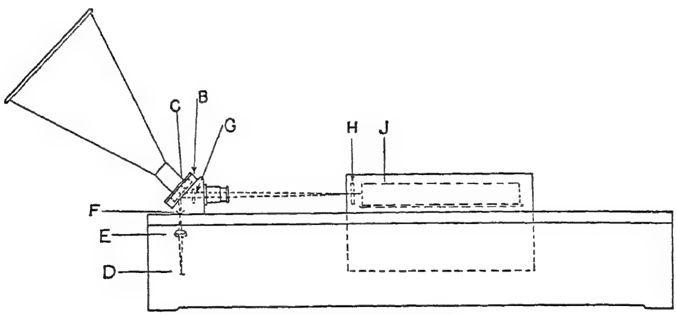


Fig. 70.—Low-Hilger Audiometer

B, Diaphragm with silvered patch to act as a vibrating mirror. D, Source of light focused by lens E on a slit F. G, Lens for producing image of slit on revolving drum J. H, Cylindrical lens with axis vertical condensing the image of the slit to a point.

Vibration of the diaphragm gives a vertical vibration of this point image which is made visible by the revolving drum. For demonstration purposes the drum is removed and replaced by a revolving mirror which reflects the beam on to a screen.

lever (fig. 69) was then made to retrace the furrow on the cylinder or disc, while the other end traced a curve on a smoked drum. By placing the pivot of the lever close to the point moving over the record, considerable magnification was obtained, and a curve which roughly corresponded to the motion of the original tracing point—and therefore the diaphragm of the recording mechanism—was produced.

This method is obviously open to very serious disadvantages. The indentation of the tracing point on the wax will follow very imperfectly the movement of the air, as the resistance of the wax will vary with the depth of the indentation, and the finer details of the air movements are likely to be blurred and obscured.

Another method of obtaining the same result is adopted in the

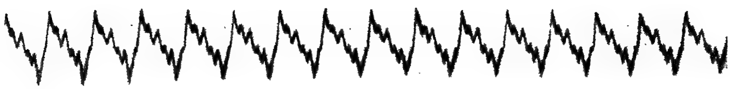


Fig. 71.—'Cello Record, open A string; frequency 230 per second

audiometer (fig. 70), designed by Professor Low and constructed by Messrs. Adam Hilger. By kind permission of the firm I have here the essential part of the apparatus, arranged so as to demonstrate the curves corresponding to various qualities of tone. The collecting horn concentrates the sound waves on an extremely light diaphragm, part of which is platinized so as to act as a mirror. The light coming from a small source at D is condensed by the lens E on a slit at F. It is then

Fig. 72.—Record of Mouth Organ

reflected from the platinized portion of the diaphragm and focused by lenses G and H, H being a cylindrical lens with its axis vertical so as to concentrate the image of the slit F to a point. When the diaphragm is set in vibration, the inclination of the reflecting portion of it alters and the spot of light oscillates vertically. The form of the vibration can be made visible to an audience by reflecting the converging beam from H on to a screen by means of a rotating mirror. In this way a characteristic curve is obtained, the form of which varies with the

quality of the tone. You will notice that as I sing into it the vowel sounds the characteristic pattern changes. Numerous of sound have been recorded in this way. Some of these are sl

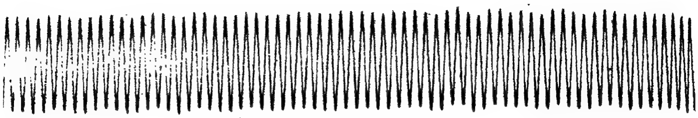


Fig. 73.—Record of Ocarina

the accompanying slides (figs. 71, 72, 73). They are not in a form, however, in which it is easy to submit them to analysis in order to find out which component tones are present, and in what strength.

Resonance.

Before following this method farther it may be well to consider an earlier method based on the principle of resonance. Resonance may be defined for sound as the response of an instrument capable of emitting a particular note when the note in question is otherwise sounded; but the phenomenon has many applications in other spheres than that of acoustics, and it may be well to consider it first in its wider aspect. Most vibrating systems have several possible modes of vibration, as we have already seen, and if disturbed and left to themselves they will, as a rule, oscillate in one or more of these with gradually diminishing amplitude. A pendulum is a case in point. A spring with a mass attached is another: the prong of a tuning-fork, the string of a violin illustrate the same point. These vibrations are termed *free*. If now to the vibrating system there is applied a periodically varying force, the system vibrates under the influence of the force and in the period of the force with an amplitude usually small. This is known as *forced* vibration. Taking an empty bottle and blowing across the top of it so as to elicit its proper note in free vibration, I pour water in until the tone of the bottle differs by about a semitone from the note of this tuning-fork. If now I strike the tuning-fork (fig. 74) and hold it over the neck of the bottle, the air in the bottle is set in vibration but gives the note of the fork and not its own proper tone. The sound is faint.

In the particular case, however, for which the period of the force coincides with the natural frequency of the vibrating system we get

resonance, and the amplitude evoked in the vibrating system may be very large indeed. It is for this reason that troops are instructed to break step when crossing a bridge. There is a danger that the timing of the tread should just happen to coincide with the natural period corresponding to one of the modes of vibration of the bridge. It is doubtful, however, whether the danger is so acute as to justify the action of a corporal who, on marching a party of two privates across London Bridge, is reported to have insisted on their breaking step.

A very beautiful illustration of forced vibration and resonance is

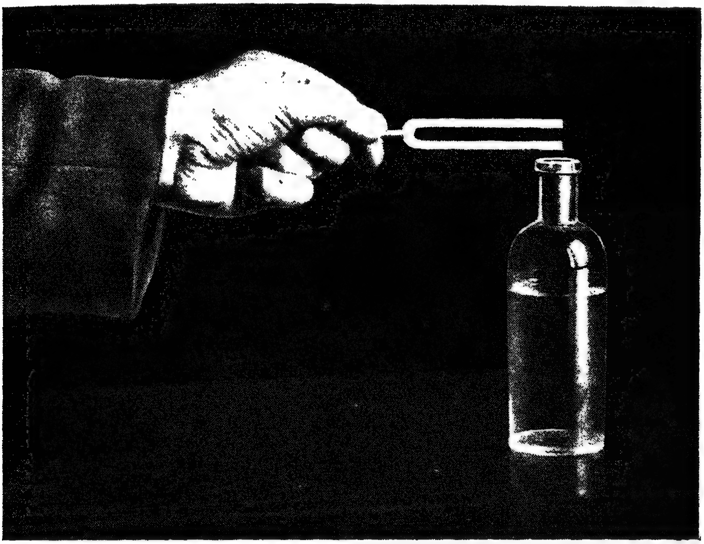


Fig. 74.—Tuning-fork used to elicit note of air contained in a bottle
The bottle is tuned by altering the amount of water in it

afforded by an unbalanced gyroscope to the frame of which is attached a series of springs of varying length. The apparatus (fig. 75) is made by Messrs. Griffin, and has been lent by them for the purposes of this demonstration. Setting the gyro wheel in rapid rotation, and placing the instrument so that the images of the ends of the springs can be projected on to the screen, we notice that at first none of the springs shows marked vibration. They are all forced to vibrate with a frequency too high for their natural frequency and their response is small. As the speed of rotation of the wheel diminishes, however, the vibration which it communicates to the frame falls in frequency and presently coincides with the natural frequency of the shortest spring. This immediately takes up a vibration of large amplitude. Presently the second shortest spring vibrates with increased amplitude while

that of t shortest dies away, and so on through the series, each in turn with maximum amplitude when the fre- enc of the frame is its own natural frequency.

The of resonance in its electrical applications is familiar f wireless sets. An electrical circuit, like a me- , has a natural frequency. In order to excite , it must be acted on by a periodic electrical

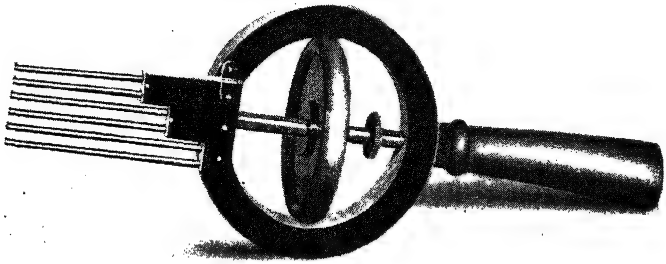


Fig. 75.—Unbalanced gyro wheel with vibrating springs attached to frame

force of its own natural frequency. Here we have two electrical circuits (fig. 76), in one of which oscillations are excited by the passage of electric sparks. Each spark sets up electrical oscillations which rapidly die out. At a short distance from this circuit is placed another which contains a small electric glow lamp. It can be tuned by altering an adjustable capacity. We see that as the capacity is diminished the electric glow lamp becomes luminous, while if the capacity is still farther diminished it goes out again.

Sharpness of Resonance.

One very important matter in connexion with resonance is what has been called the *sharpness* of resonance. If we take a bottle tuned to a particular frequency and hold a series of tuning-forks successively opposite its mouth, we shall find that it responds not merely to the fork which is in tune with its natural frequency, but to forks differing in pitch from this by a tone or more. On the other hand, in the case of two tuning-forks where resonance is so marked when the forks are correctly tuned, the slightest mistuning—a tenth of a tone or less—makes the response almost negligible. Thus we find, in the case of the bottle, a response to all neighbouring pitches without very marked response to any, and in the case of the forks a highly selective action involving very marked response for correct tuning, and almost no response for quite small differences in pitch from the correct value.

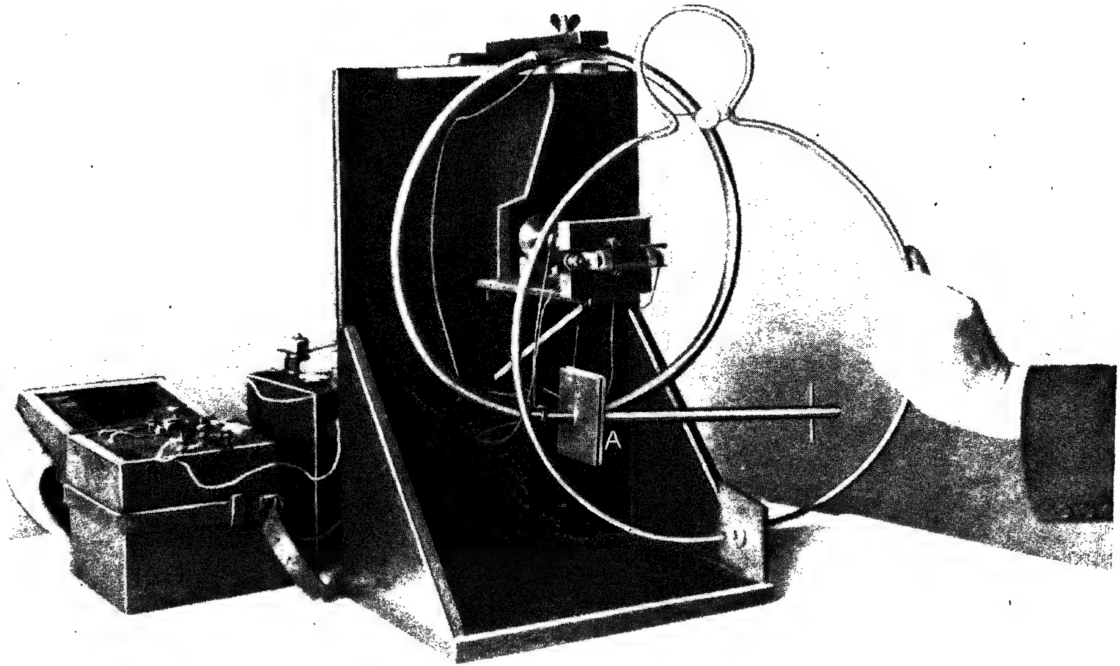


Fig. 76.—Electrical circuits for illustrating resonance

A, Adjustable capacity for tuning fixed circuit. B, Lamp in movable circuit which lights when tuning is exact

This difference is bound up with the *damping* of the system, i.e. with the rate at which its free vibrations die out when it is disturbed and left to itself. In the case of the bottle we can produce a tone by blowing across the neck, but the tone ceases almost at the instant at which the air blast is stopped. On the other hand, in the case of the fork we start the free vibrations by plucking or bowing the prongs, and the sound persists for quite a long time afterwards.

The phenomenon is very well illustrated by an experiment due to Barton. From a stretched horizontal cord a number of light pendulums are suspended (fig. 77). These pendulums vary in length ;

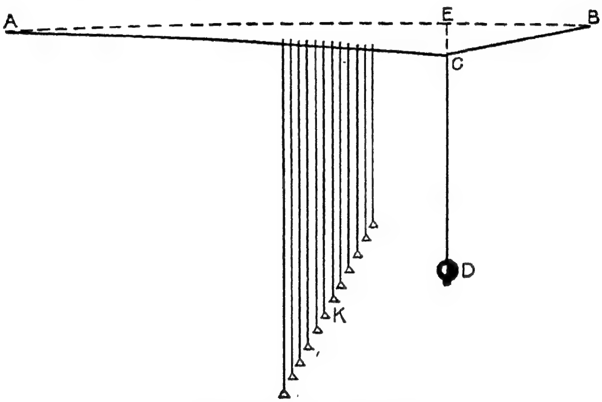
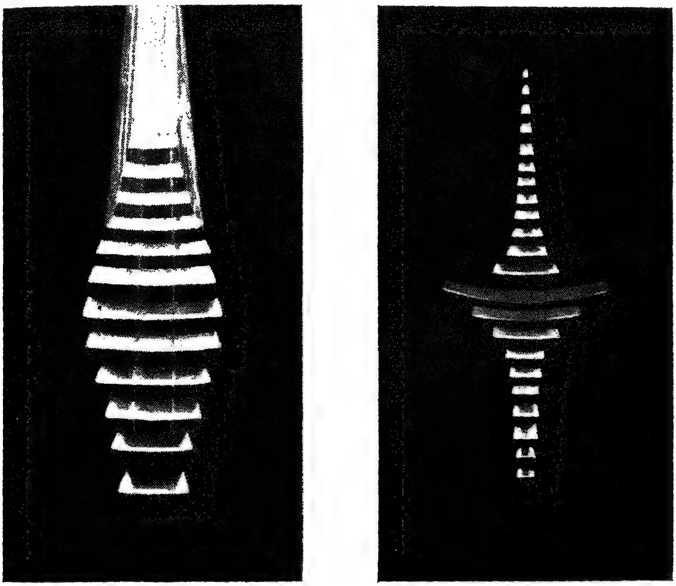


Fig. 77.—Barton s Pendulums

ACB, Stretched cord. D, Heavy pendulum bob suspended from the cord. K, Light paper cones suspended by threads from the same cord and set in motion when D is made to swing. DE is the effective length of the driving pendulum.

consist of small paper cones attached to threads. At some distance from them is suspended a heavy iron bob, forming a pendulum of length intermediate between the longest and shortest of the light pendulums. If now the heavy pendulum is set swinging, its motion is communicated to the light pendulums, which presently settle down to forced vibrations. One of them, the correctly tuned one, has the largest amplitude, but its amplitude is not notably greater than that of its neighbours. Here the damping is fairly great, and the vibrations when not forced by the large pendulum die out fairly rapidly. If now we slip on to the paper cones split curtain rings, we reduce their rate of damping, and it will be found that their swings, when once started, now persist for a much longer time. This will be understood if we consider that when we displace them to start them in motion, we have to do more work on them owing to their greater mass, and we therefore give them a greater initial store of energy. On the other hand, the

work which the pendulums do against the air resistance in each swing is practically the same as before, so that, while the initial energy is greater, the rate of loss of energy is unchanged and therefore the damping is less. We shall now find that the correctly tuned pendulum swings with an amplitude which is notably greater than that of its neighbours. This effect will be obvious from the photographs in fig. 78, which were taken during the swinging—the camera being directed



(a) (b)

Fig. 78.—Photo of moving pendulums in Barton's experiment, showing variation of amplitude

a, Cones unloaded and therefore heavily damped showing little selective resonance.
b, Cones loaded with curtain rings, giving small damping and selective resonance.

from the left-hand side of fig. 77 so that the pendulums are seen one above the other and swinging perpendicular to the line of sight. The arcs of circles represent the amplitudes of the various pendulums in the two cases. The sounding-board of a piano and the body of a violin are examples of vibrating systems with large damping, which therefore respond nearly evenly to all the notes of the musical scale. Taking two tuning-forks in exact unison and mounted on resonance boxes, we place them with the openings of the boxes opposite one another. On bowing one fork strongly and then stopping it by touching the prongs, the second fork is found to be sounding. Releasing the first fork and damping the vibrations of the second, the first fork is again found to

be sounding. In this way the energy can be passed from one fork to the other and back again three or even four times if the tuning is accurate. If, on the other hand, we very slightly lower the pitch of either fork by loading it with a little wax the resonance is almost completely destroyed.

Air Resonators.

An air cavity—such, for example, as the interior of a bottle—may act as a resonator, as we have already seen. It can be tuned either by diminishing its volume, which raises its pitch, or by diminish- the aperture of the mouth, which lowers the pitch. The first of these principles is illustrated every time we fill a jug or bottle at a tap. The

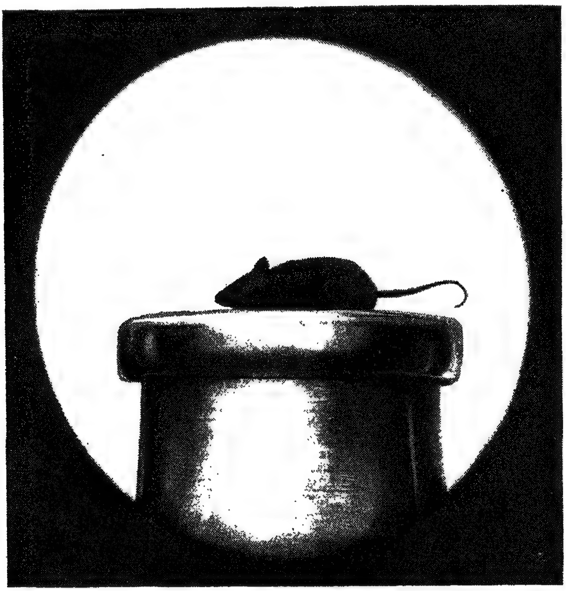


Fig. 79.—Projection on screen of paper mouse resting on membrane partially closing the mouth of a resonance bottle

When the correct note is sounded the membrane is set in vibration and the mouse is shaken into the bottle.

pitch of the resulting note gradually rises until, when almost full, the pitch runs rapidly up the scale. This method of tuning may be illustrated in a more spectacular way. A wide-mouthed bottle has the mouth half closed by a piece of tissue paper stretched over it, and waxed in position without being stretched too tightly. An organ pipe a little too sharp in pitch is then selected, and a paper mouse, cut with a small base, is placed on the tissue paper. The mouse is projected

on the screen by means of the lantern (fig. 79), and the bottle tilted so that the paper slopes down towards the open half of the mouth. When the pipe is sounded the mouse shows no sign of agitation, but if water is slowly run into the bottle the agitation of the mouse becomes apparent, and goes on increasing until at last it rushes down the paper and disappears into the bottle. The other method of tuning is illustrated by taking an ordinary drinking-glass and holding over it a vibrating fork. A post card is now gradually passed across the mouth of the glass until at one point the sound of the fork swells out. The air cavity is now tuned to the fork. If this is done for several forks the principle just indicated is verified.

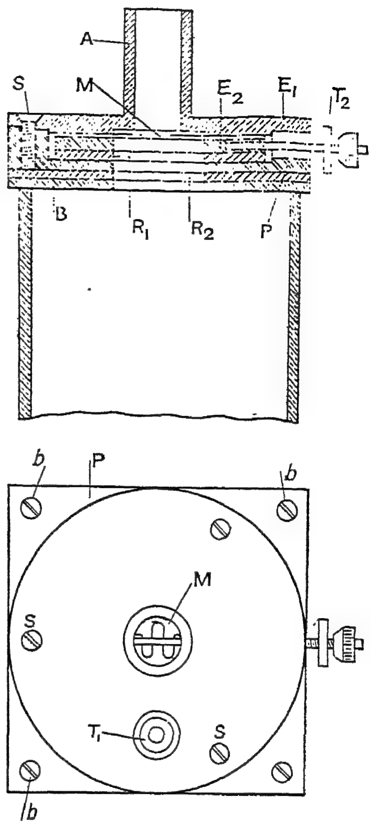


Fig. 80.—Tucker Selective Hot-wire Microphone

A, Cylindrical neck of resonator. E_1, Brass plate carrying terminal T_1 and making contact with one end of the resistance wire. E_2, Brass plate insulated from E_1 carrying terminal T_2 and making contact with the other end of the resistance wire. M, Mica plate carrying the resistance wire, one end of which finishes above the mica and the other below. R_1, R_2, Rubber rings with ebonite P clamped in position by screws at S. Resistance wire is heated by a current sent between the terminals T_1 and T_2. The volume of the resonator fixes the pitch.

Analysis by Resonators.

The detection of the resonance of the air contained in a resonator may be observed and measured in a much more accurate and scientific manner. During the war the position of enemy guns was obtained by a process known as sound-ranging, which depended on recording the receipt of the report of the firing at a series of points spaced along the arc of a circle. At each point is placed a large hollow container with a small neck. Across this neck there is stretched a grid of very fine wire, through which an electric current is passed sufficient to heat the wire to a red heat. When the sound wave due to an explosion passes across the aperture, air is driven into and out of the container by the change of pressure. This draught of air cools the wire and so lowers its electrical resistance, and the change of resistance is electrically recorded. This hot-wire microphone was devised by Major Tucker, and

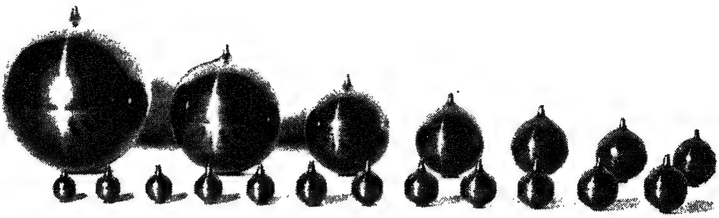


Fig. 81.—Helmholtz Resonators

in this form is not selective, that is to say, it does not respond to a selected frequency. It has, however, been adapted by its inventor to

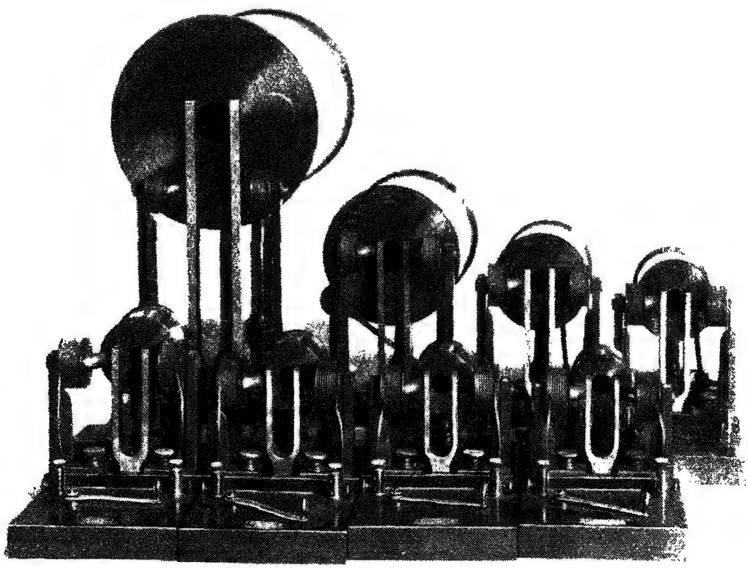


Fig. 82.—Set of electrical driven forks with resonators giving the harmonic series used by Helmholtz for the synthesis of vowel and other sounds

the detection of frequency by fixing a grid in the neck of a cylindrical resonator tuned to a definite pitch (fig. 80). The arrangement is then

highly selective and very sensitive, responding to notes of such feeble intensity as to be inaudible to the normal ear, and it can be used with great gain of accuracy as a substitute for the Helmholtz resonator.

The Helmholtz resonator is shaped rather like a turnip. At the root end is a small aperture which is inserted into the ear. At the other end is a larger aperture directed towards the source of sound. If the sound contains a partial whose natural frequency is that of the resonator, it will be picked out and reinforced. Thus, using a series of these resonators (fig. 81), we can find which partial tones are present in a complex sound, and get some rough idea of their relative strength.

Helmholtz carried out a number of analyses using this method, and applying it to the investigation of vowel sounds and other types of musical quality. He also checked his results by maintaining electrically a series of tuning-forks corresponding to the harmonic series (fig. 82). The intensities were adjusted by partially uncovering the apertures of resonators tuned to the various forks and situated immediately behind them. In this way he synthesized the sound which he had previously analysed, and met with a surprising amount of success, considering the difficulties and limitations of the method he used.

Miller's Phonodeik.

Proceeding now to more exact methods of analysis, we come to an instrument known as the phonodeik, devised and used by Professor

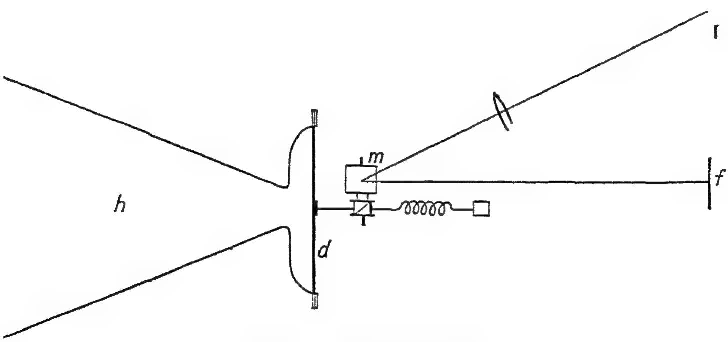


Fig. 83.—Miller's Phonodeik

A, open end of horn *h*. *d*, Thin glass diaphragm. *m*, Small mirror mounted on cylindrical steel staff rotating in jewelled bearings. The fine wire from the mid-point of the diaphragm passes once round the staff and is held in tension by the spring. I, Source of light focused on to *m*, from which the beam is reflected on to a vertically moving film *f*.

D. C. Miller. Its mechanism will be understood by reference to the diagram (fig. 83). The horn A collects the sound and concentrates it on the very fine glass diaphragm of thickness about ·0076 cm. To the centre of this diaphragm is fixed a very fine wire, which passes once

round the vertical steel is held taut by a light spring. To the staff is fixed a very small mirror about 1 mm. square. The varying pressure in the sound wave causes vibration of the diaphragm, and this vibration in turn pulls and releases the attached wire, so causing rota-

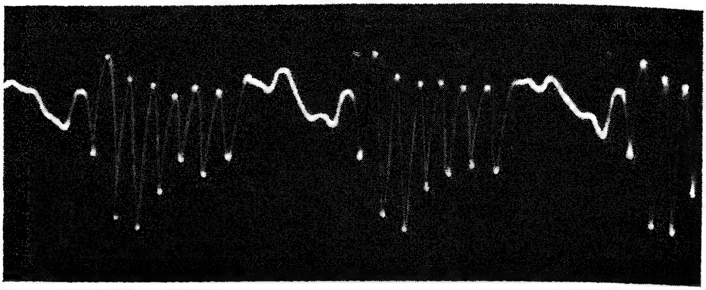


Fig. 84.—Photograph of the tone of a clarinet

on of the steel staff and mirror. A beam of light from a fixed source is reflected from the mirror on to a vertical strip of film, where it is focused. The rotation of the staff will thus produce a horizontal oscillation of the image of the mirror, and if the film is made to move vertically the spot of light will trace on it a curve which reproduces the

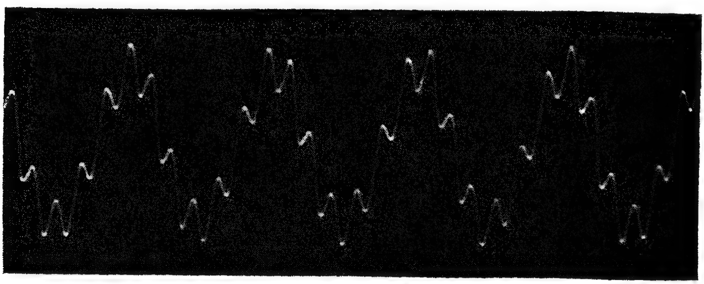


Fig. 85.—Photograph of the clang tone from a tuning-fork

phragm would produce
Using this instrument, urves corre-
sponding to the human usical instruments, and
some of these are shown in the slides (see figs. 84, 85,
86, 87, 88).

The difficulty about this instrument, as about all instruments devised for analysing sounds, is to be sure that the response of the instrument is uniform over the whole frequency range, so that the various

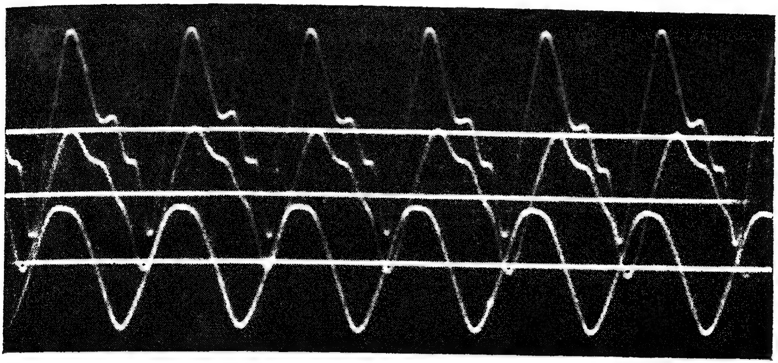


Fig. 86.—Photographs of the tones of a flute, played *p*, *mf*, and *f*

components will preserve their relative intensity. The diaphragm, for instance, will have a series of natural frequencies corresponding to different partial tones, some of which have been studied by Chladni's

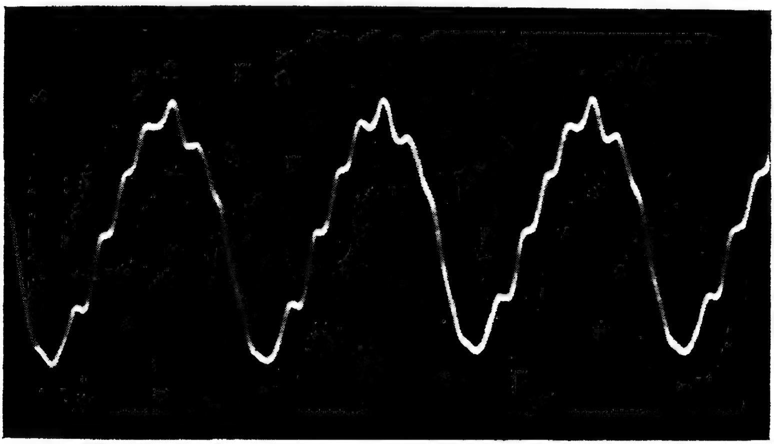


Fig. 87.—Photograph of the tone of a violin

sand-pattern method, and photographs of some of the patterns for a telephone diaphragm are shown in fig. 89. Clearly, any component tone having a frequency coinciding with that of one of these partials will produce a disproportionate response in the instrument, and will

appear in the ultimate analysis with its intensity greatly exaggerated. The horn is open to the same objection, as is also the air cavity at the end of the horn in which the diaphragm is housed.

The only effective method of checking the response of the phonodeik is to produce a series of pure tones of the same intensity, distributed over the whole frequency range, and measure the response in each case. At the time when the phonodeik was first used there was no simple method available for producing pure tones of known intensity, and Professor Miller had a series of organ pipes specially designed by an expert to give equal loudness of tone. With this series he calibrated

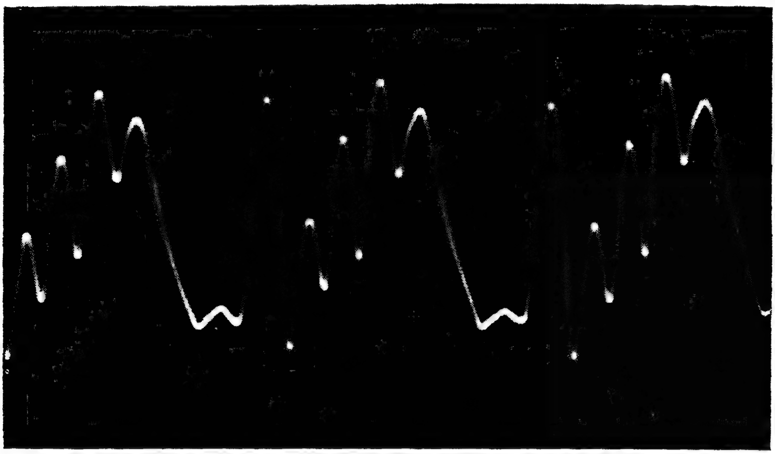


Fig. 88.—Photograph of the tone of an oboe

the phonodeik, and used this calibration curve to correct the results of the analysis.

Perhaps the most striking result which emerged from his experiments was that the constituent partial tones in a musical note did not form a series of descending intensity as had usually been assumed. The distribution of energy between the partials was found to vary greatly for different sources of sound, and in some cases high partials carried a large proportion of the energy, as for instance in the clarinet, where the eighth, ninth, and tenth partials were found to carry 18, 15, and 18 per cent respectively of the total energy, so that practically one-half of the energy appeared in these very high order partials. In the case of the oboe the fourth and fifth partials carried 30 and 36 per cent respectively, or two-thirds of the total energy between them. The fundamental, giving the pitch of the resulting sound, was found to carry a negligible proportion of the energy in this case.

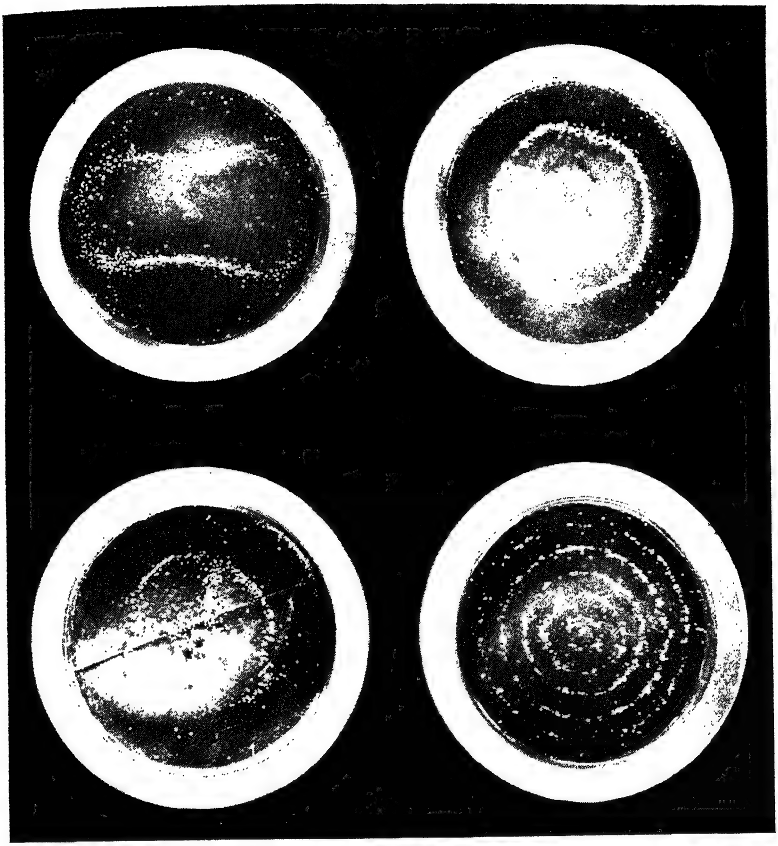


Fig. 89.—Different modes of vibration of a diaphragm shown by sand figures

Analysis of Vowel Sounds.

According to Tyndall, the question of how we distinguish one vowel sound from another when both are sung to a note of the same pitch and of equal intensity was made a prize question by the Academy of St. Petersburg in 1769, and the prize was awarded to Kratzenstein for the successful manner in which, by mechanical arrangements, he imitated the vowel sounds. The question was subsequently taken up by Willis, Wheatstone, and Helmholtz.

Experiments with the phonodeik made an important contribution to the study of vowel quality. The vowel sound *a* in the word " father " was sung by various voices to notes of different pitch, and the analysis carried out in each case. It was found that when the vowel was intoned at a frequency of 155, the sixth partial carried 69 per cent of the total

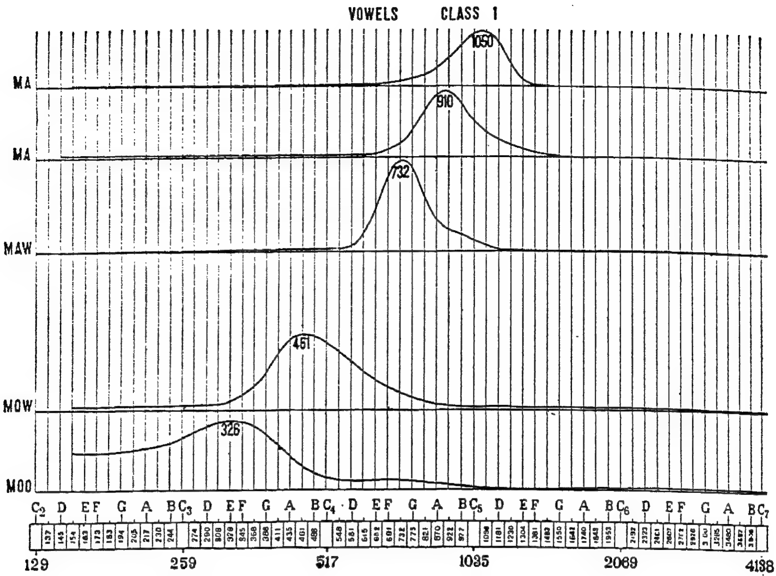


Fig. 90.—Characteristic curves for the distribution of the energy in vowels having a single region of resonance

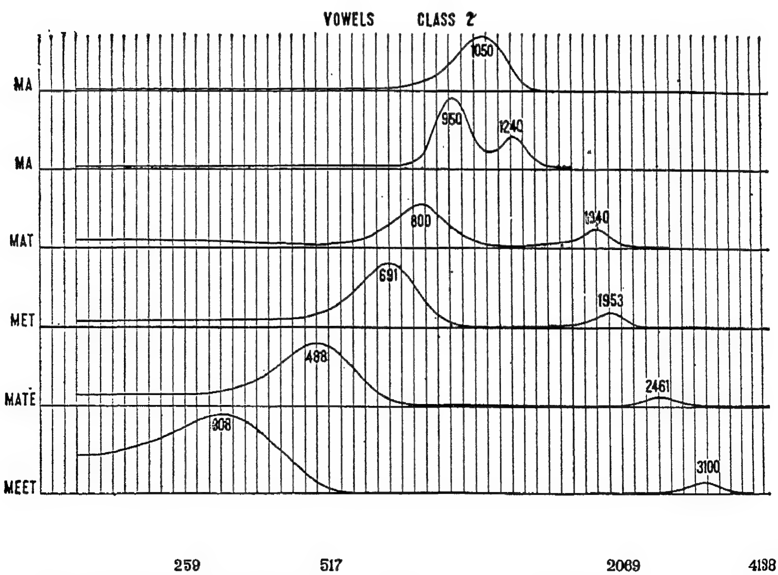


Fig. 91.—Characteristic curves for the distribution of the energy in vowels having two regions of resonance

energy. When intoned at frequency 182, the fifth partial was loudest and carried 48 per cent of the energy; while intoned at a frequency 227, the fourth partial was loudest and contained 65 per cent of the energy. It will be noticed that the actual pitch of the strong partial is nearly the same in the three cases:

$$6 \times 155 = 930$$
$$5 \times 182 = 910$$
$$4 \times 227 = 908$$

Professor Miller's observations showed that in all cases this general rule held, and that whatever the frequency of the note on which the

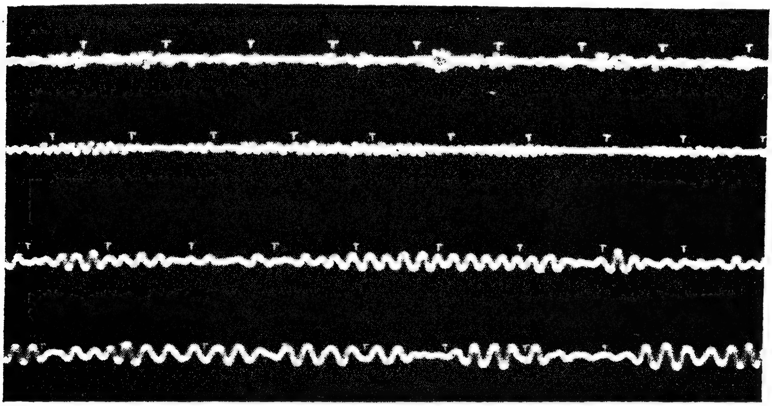


Fig. 92.—Photographs of Whispered Vowels

vowel sound was produced, the strong partial was the one which came nearest in pitch to a frequency 910. Extending this investigation to other vowels, Professor Miller arranged them in two series, in one of which they seemed to be characterized by loud partials in one particular region of pitch, while in the other they were characterized by two such regions. The results of the analyses are shown in figs. 90 and 91. If we attempt to pronounce one of these series of vowel sounds we shall find that each series is produced by a progressive movement of the mouth and tongue.

These results were confirmed in three different ways. If, for instance, we take the vowel sound *ow* as in "mow", we see that it belongs to the series which has one principal region of resonance in the neighbourhood of 461. If now we sing this vowel sound on any given note and record it on a gramophone record, then when the record is run at the proper speed the vowel sound will be accurately reproduced. If, however, the record is run more slowly the sound will tend to become $\overline{oo}$, whereas if the record is run more quickly it will tend to

become *aw*. This variation of the characteristic region of resonance when a gramophone record is run at the wrong speed accounts for the extraordinary distortion of speech sounds which results. The experiments not only verified the change in vowel quality but gave a good numerical check for the frequencies characterizing the four vowels of ;.

:r method of check was to obtain phonodeik records of whispered vowel sounds (fig. 92). In this case the voice tones are absent, and the record consists mainly of small vibrations characteristic of the vowel. These were counted and confirmed the original observations.

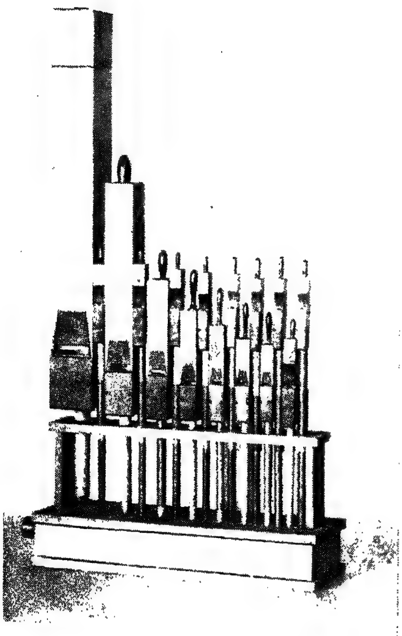


Fig. 93.—Pipes for synthesis of vowel *a* in *mat*

Lastly, the vowel sounds were synthesized (fig. 93), using a series of specially designed stopped organ pipes such that the loudness of tone could be adjusted. Synthetic vowel sounds when judged by ear are difficult to appraise, but in this case they were not merely judged by ear but were used for the production of a phonodeik record, which was compared with that of the original sound and found to show a very fair agreement.

Electrical Methods of recording Sounds.

An entirely different method of analysis has been adopted in the Bell Telephone Laboratories. In this method the speech waves were picked up by a telephone transmitter and converted into electrical waves, great care being taken to design a transmitter in which the electrical waves would faithfully reproduce the original sound waves. These electrical waves were then magnified by a specially designed amplifier and delivered to an oscillograph, where they caused a tiny ribbon to vibrate in a way which exactly reproduced the form of the original air waves.

This record was photographed, and an example of it is given in fig. 94 for the word "farmers". It will be seen that the first letter *f* is characterized by very high frequencies. After these high frequencies the *a* sound is produced by only 5 complete waves, having a

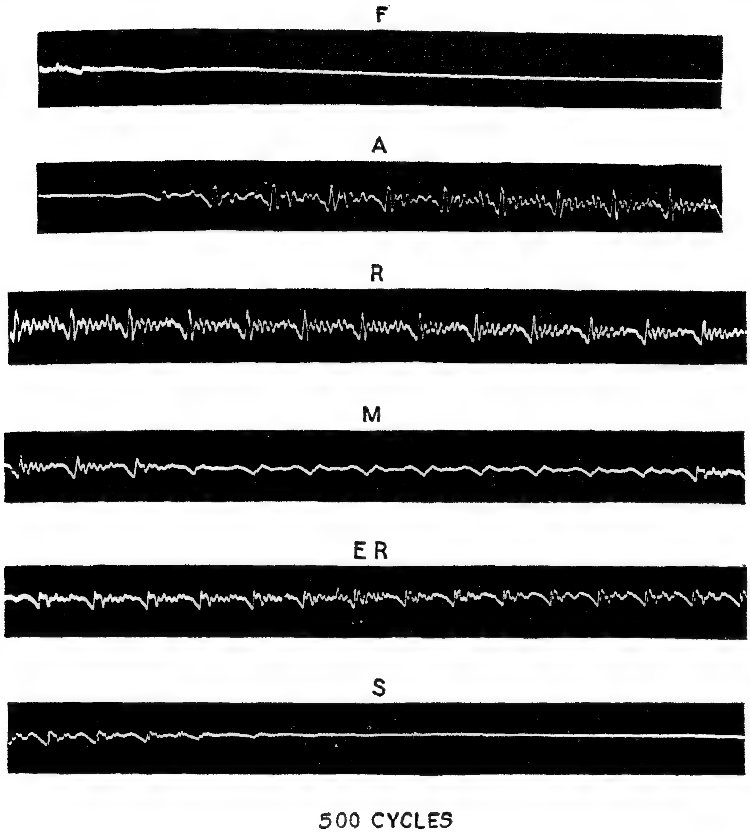


Fig. 94.—Wave form of the word "farmers"

fundamental frequency corresponding to approximately 120 cycles per second. The *r* sound is followed by about 20 complete waves having this same fundamental frequency, followed by about 9 complete waves of the *m* sound, also with the same frequency. As the *er* sound was reached, the pitch of the voice was slightly raised to a pitch corresponding to a fundamental frequency of about 130 cycles per second.

This was followed by the *s* sound, again characterized by very high frequencies. The wave form of the word "poor" is shown in fig. 95.

In the case of musical sounds and vowel sounds the analysis has been carried out by Wegel and Moore, using a very ingenious but very complicated instrument known as the electrical frequency analyser. This instrument analyses directly the electrical waves into which the sound waves are transformed, with enormous economy of time and trouble. The whole analysis can be carried out in a very few minutes, the harmonic components of the electrical waves being registered.

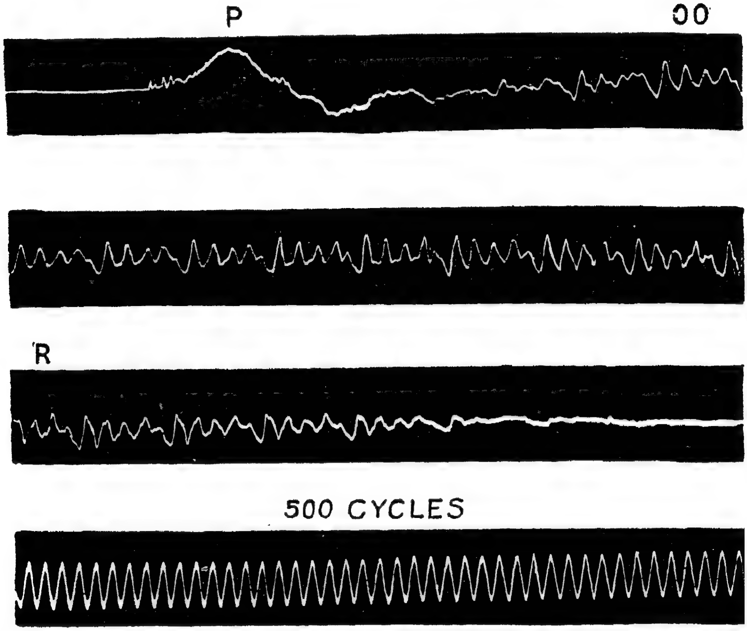


Fig. 95.—Wave form of the word "poor"

If the original waves have been faithfully transformed into electrical waves (and great care is taken to secure this), then the result of the analysis will be applicable to the original sound.

The general results obtained confirm the work of Miller with the phonodeik, except that all the vowels seem to be characterized by two resonance regions, the region of higher pitch being much less important in the case of the series to which Miller assigned only one resonance. The acoustic spectra of the vowel sound *e* as in "eat" are shown in fig. 96 for four different fundamental pitches, and it is obvious that in each case the partials are strongly reinforced in the neighbourhood of 2000 and 2250. According to Crandall there is in the spoken vowel "a period of rapid growth in amplitude lasting about ·04 sec.,

during which all components are quickly produced and rise nearly to maximum amplitude; second, a middle period lasting about ·165 sec., followed by the period of gradual decay lasting about ·09 sec., bringing the total length to approximately ·295 sec."

It is not surprising to find that there is not exact agreement in the analyses obtained for different voices. Pronunciation varies with

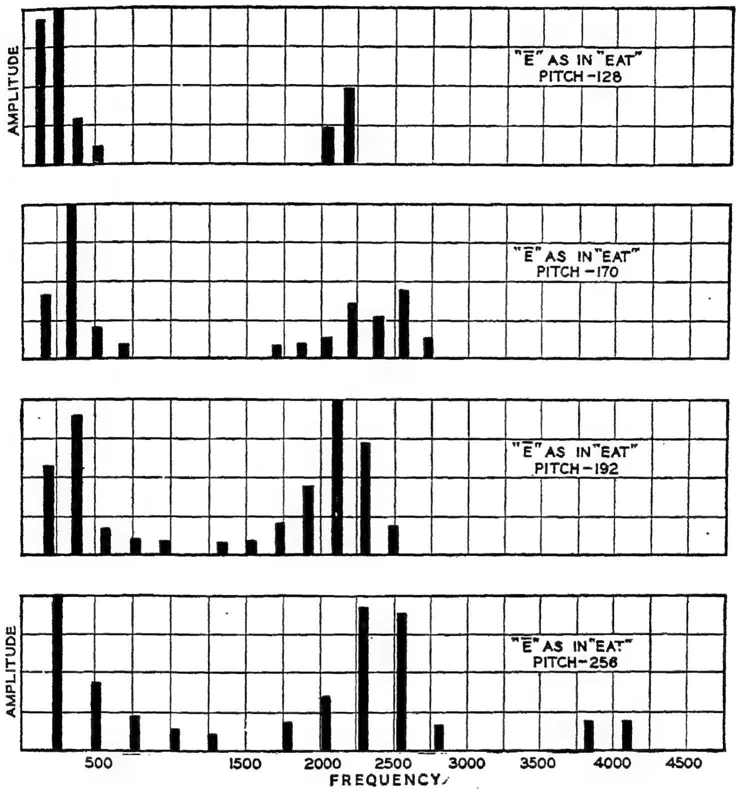


Fig. 96.—Electrical analysis of vowel sound *e* as in " eat ", showing marked concentration of energy in the frequency region 2000 to 2500

different individuals in a quite notorious way, and these differences are reflected in the individual analyses which have been made; but the fundamental agreement leaves no doubt that vowel sounds are defined in the way indicated, and this has an important bearing on the subject of phonetics. It is now possible to register the component frequencies for the vowel sounds in different languages and dialects, and thus to obtain a scientific basis of classification.

Some results of the analysis of musical sounds are given in fig. 97.

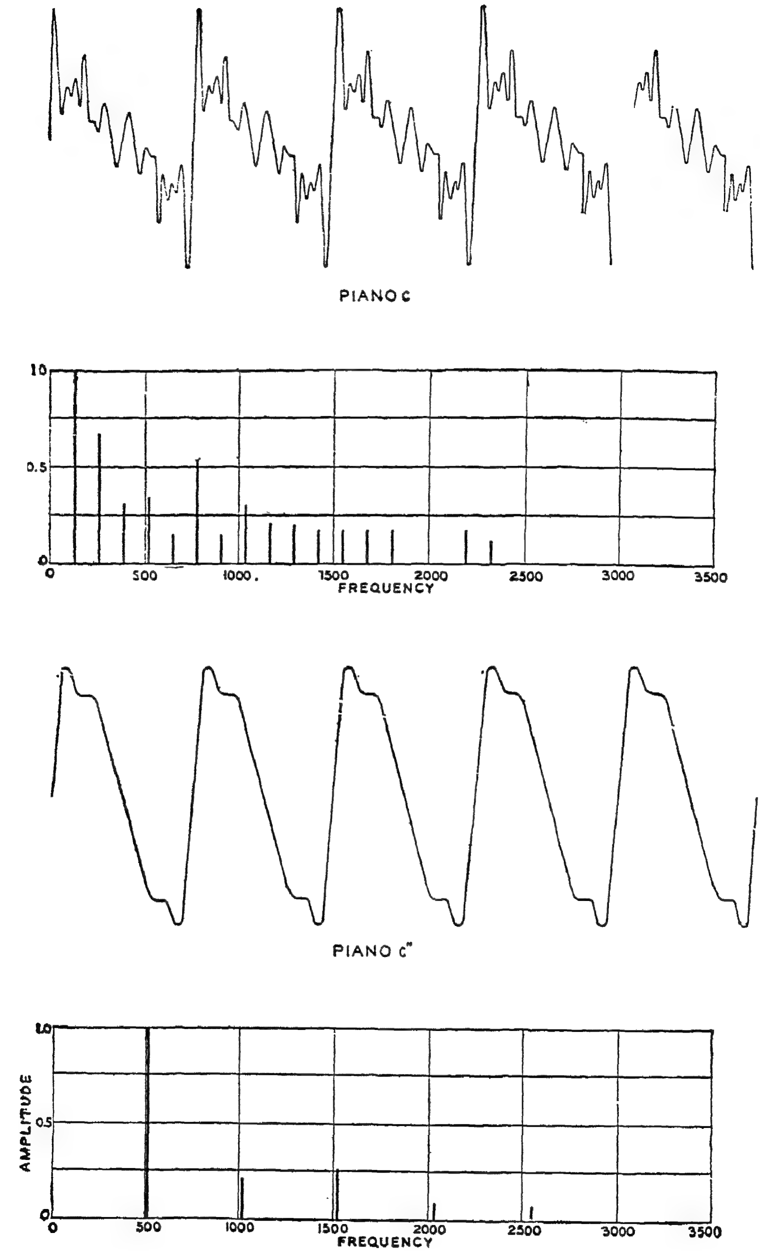


Fig. 97.—Electrical analysis of the tone of a piano showing partials for the note C up to the 18th

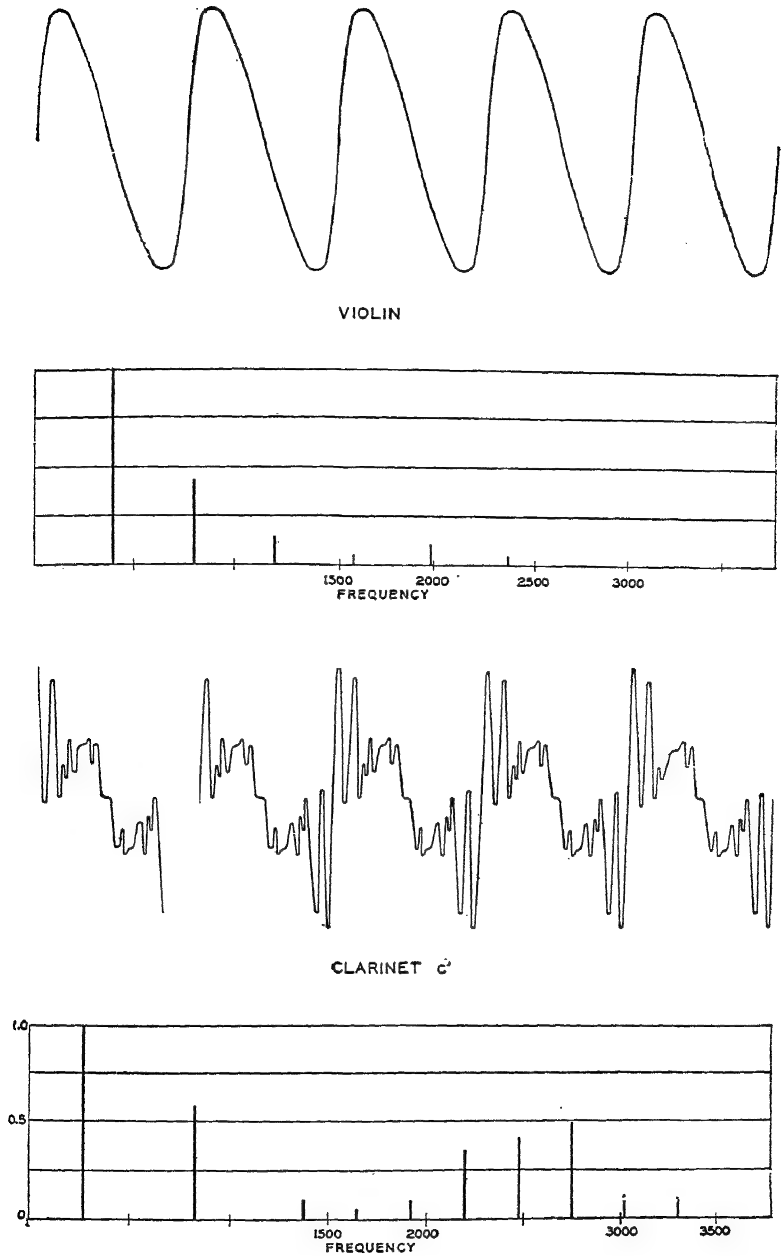


Fig. 98.—Electrical analysis of the tones of a violin and clarinet showing strong eighth, ninth, and tenth partials for the latter

The spectrum is given below in each case and the corresponding graph is given above, but in the case of these figures the graph is not obtained directly, but is constructed from the analysis on the assumption that all the component partials have the same phase, i.e. all the vibrations start from their zero position at the same instant, so that all the curves

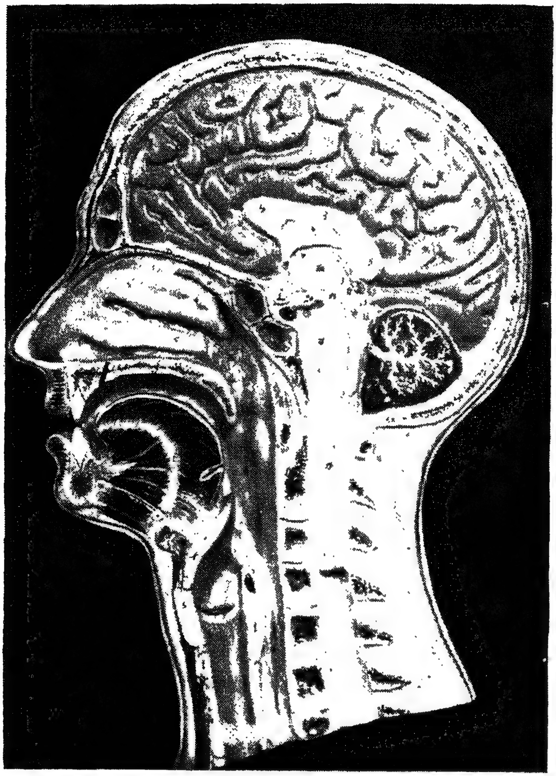


Fig. 99.—Photograph of model section of the head, showing air cavities of mouth and pharynx

cross the axis at the same point. We should get a different wave form if we altered the relative phases by moving the curves relative to one another along the axis, but the work of Helmholtz and others goes to show that this in no way affects the musical quality, which depends only on the number and relative intensities of the partials and not on their relative phases. It will be noted in the case of the clarinet (fig. 98) that the second and fourth partials are missing, but that the eighth, ninth, and tenth are particularly strong, a result which we have already noted in the analysis given by Miller.

Synthesis of Vowel Sounds.

The constitution of the vowel sounds has been approached in an entirely different way by Sir Richard Paget. A glance at the model of the vocal organs (fig. 99), kindly lent by Messrs. Griffin & Tatlock, will make clear the origin of the two resonance regions which define a vowel sound. The tongue divides the mouth and pharynx into two air cavities; each of these has its appropriate note, and this note will appear in the vowel sound when sung or spoken, either by the cavity reinforcing the harmonic partial of the fundamental tone which comes

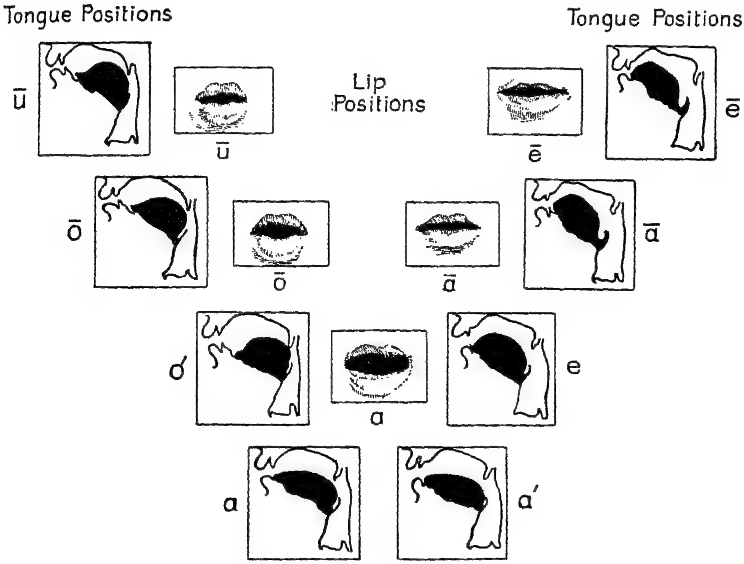


Fig. 100.—Tongue and lip positions for two series of vowel sounds

near its own natural pitch, or by giving its own natural pitch owing to the contained air being set in vibration by the puffs issuing from between the vocal cords. The changes in position of the tongue and lips are shown in fig. 100. The proper tone of the front cavity is easily elicited. If the mouth is set successively for pronunciation of the vowels *a*, *ó*, *ō*, *ū*, and the cheek tapped with a pencil, the proper tone is clear and distinct. It is also elicited by bringing the hands smartly together just in front of the mouth, and so driving a wave of air past the aperture between the lips. The proper tone of the back cavity is harder to elicit, but Sir Richard Paget can produce it without difficulty and is able to produce two tones simultaneously in such way as to sing a duet by himself. By using plasticine, he produced double resonators (fig. 101) in which the proper tone of each was adjusted so as

to give the resonance pitches for the various vowel sounds. The part of the vocal cords was played by a reed, and air was driven from this reed into the double resonator. We have here some of Sir Richard Paget's later models made in cardboard instead of plasticine, and when these are mounted on a wind-chest and blown, the reproduction of the

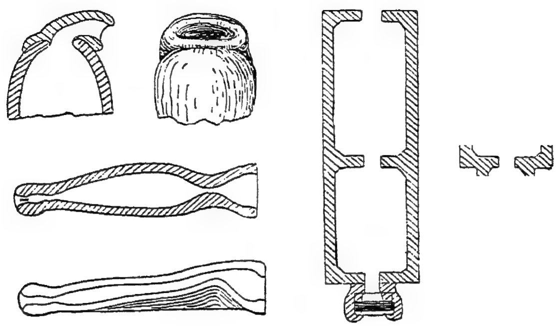


Fig. 101.—Sir Richard Paget's models for the production of vowel sounds

various vowel sounds is extraordinarily faithful. By interrupting the air blast in various ways, consonants can be prefixed to the vowel sounds and simple words produced. Fig. 102 gives the results of Paget's experiments on the vowel sounds, and it will be seen that he finds them all to be characterized by double resonance. The annexed table combines the results of Paget and Crandall, one set being obtained by

NATURAL OR CHARACTERISTIC FREQUENCIES OF THE VOWEL SOUNDS

(Male Voices)

Sound.	Frequency of Lower Resonance.				Frequency of Upper Resonance.			
	Crandall and Sacia.	Paget, centred about	Mean.	Equiv. Pitch.	Crandall and Sacia.	Paget, centred about	Mean.	Equiv. Pitch.
oo (pool) ..	431	383	407	G_3	861	724	793	G_4
u (put) ..	575	362	473	B_3	1149	966	1058	C_5
o (tone) ..	575	430	502	C_4	912	790	851	A_4
a (talk) ..	645	558	602	D_4	1024	886	955	B_4
o (ton) ..	724	703	713	F_4	1218	1116	1167	D_5
a (father) ..	861	790	825	G_4	1149	1254	1202	D_5
ar (part) ..	861	769	814	G_4	1290	1491	1390	F_5
a (tap) ..	813	703	758	G_4	1825	1824	1825	A_5
e (ten) ..	609	527	568	D_4	1825	1932	1879	B_5
er (pert) ..	{542 700	470	{506 700	C_4	1448	1534	1491	G_5
a (tape) ..	609	470	540	C_4	2048	2169	2108	C_6
i (tip) ..	512	362	437	A_3	2170	2298	2234	C_3
e (team) ..	431	332	381	G_3	2435	2434	2435	D_6

analysis and the other by synthesis, and the general agreement shown in the table places the explanation of the nature of vowel sounds beyond any reasonable doubt

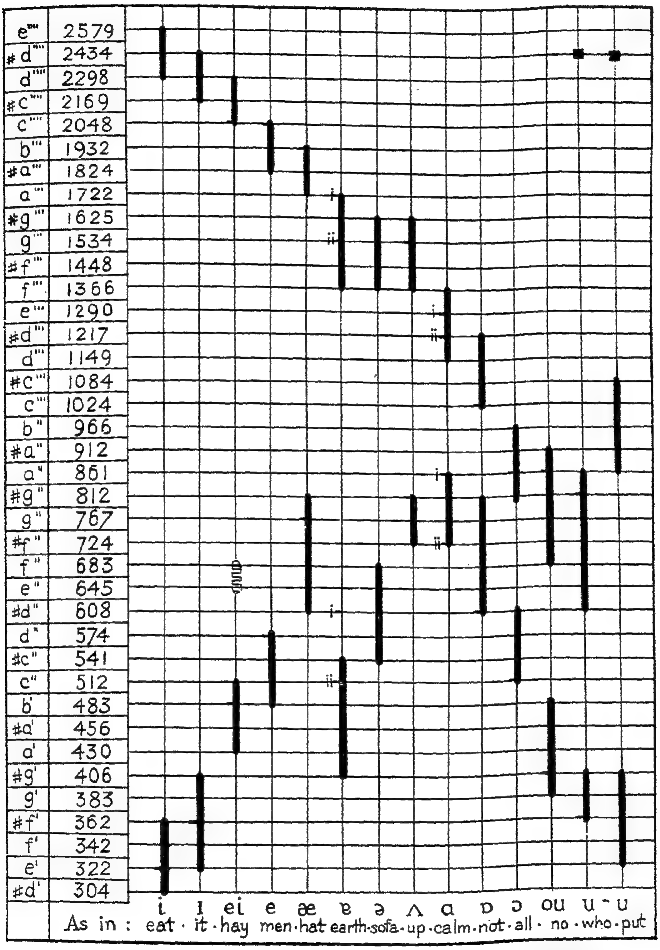


Fig. 102.—Resonance regions defining the vowel sounds as obtained synthetically by Sir Richard Paget

The consonantal sounds are more difficult to analyse, but Paget finds that *k* contains a component of frequency about 3000; *th* has frequencies between 2500 and 3400; *sh* has frequencies greater than

3000; *f* contains frequencies between 5000 and 6000; while in the case of *s* there are frequencies in excess of 6000. On the other hand, the strong frequencies in the nasal consonants, *m*, *n*, &c., may be below 200.

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tuned to its particular pitch. He conceived the main difference to be that, the fibres of the basilar membrane being damped, resonance was not sharp, and a *group* of fibres differing somewhat in natural frequency would respond to any particular tone, the short ones near the oval window to high tones and the long ones near the helicotrema to deep tones. The pitch of the tone would thus be sensed by the position in the basilar membrane of the fibres most strongly stimulated, these communicating their motion through the corresponding rods of Corti to the hair-like nerve endings. A complex note would produce a series of stimuli, giving a series of points of maximum stimulation in the basilar membrane. The power of analysis which the ear undoubtedly possesses is thus explained by the fact that we can direct attention at will to the sensation received from any particular group of fibres, and so perceive separately each constituent tone.

On this view we can think of the inner ear as equivalent to a long series of Helmholtz resonators which register the constituent partial tones in any complex sound.

Many alternative theories of the action of the ear have been proposed, and one, which has much to commend it, has been developed by Roaf and Fletcher. According to this theory, if the motion of the stirrup is slow the fluid in the inner ear moves as a whole, passing through the helicotrema and driving out the membrane which covers the round window. On the other hand, such is the density of the fluid columns filling the inner ear that if the motion of the stirrup be extremely rapid, practically no motion will be communicated to the liquid, and the energy will pass from the oval window to the round window through the neighbouring part of the basilar membrane. For intermediate frequencies varying lengths of column will be set in motion, and the energy will pass from the scala vestibuli to the scala tympani through the basilar membrane, the point of maximum stimulation of the membrane occurring at a point which is more remote from the oval window as the frequency of the applied motion becomes less. A complex note will produce a series of points of maximum stimulation. It will at once be seen that the essential feature of this view is identical with that of Helmholtz, namely, that the perception of frequency is localized in the basilar membrane, high frequencies stimulating points in the membrane near the oval window and low frequencies points at the remote end of the membrane, and both regard the power of analysis as due to the fact that a complex note stimulates a series of regions of the membrane corresponding to the frequencies of its constituent tones.

Range of Audible Notes.

It has long been known that the ear is sensitive only to musical notes within a certain range of pitch. The limits of this range have

been placed differently by different experimenters. These differences are no doubt due in part to the fact that individual differences exist. It is well known, for instance, that the upper limit of audibility is higher in children, and that by a merciful dispensation of Providence older people are much less sensitive to high-pitched sounds. The differences are also probably due in part to the fact that until recently no account was taken of loudness, and the limits of audible pitch vary with the loudness of the notes used in the test. The ear is very sensitive to small changes of pitch, and it is found that in the neighbourhood of a frequency of 500 the ear can detect a change in pitch of one-third of one per cent. Since a tone corresponds to a change of about ten per cent, this is equivalent to a discrimination of about one-thirtieth of a tone. This is, of course, only possible under favourable conditions, but one-twentieth of a tone is fairly easily detected.

With regard to loudness, the sensitiveness of the ear is very remarkable. At the most sensitive pitch the ear will detect periodic pressure changes of less than one-thousandth of a dyne per square centimetre. As the normal pressure of the air in the atmosphere and therefore in the outer ear is about 1,000,000 dynes per square centimetre, this means that if a periodic change of one-thousand-millionth part occurs in the value of the pressure, the ear will respond. It has been shown that to stimulate the ear the necessary energy flow is of the same order of magnitude as that required to stimulate the sense of sight.

Another interesting fact brought out by recent work is, that not only do we have a lower limit to the loudness of a sound but an upper limit also. If the ear is stimulated by a pure tone and the loudness of the tone increased, a point is reached at which a prickling sensation is felt and further increase becomes painful. The pressure waves are thus felt rather than heard. Also at this loudness or somewhere near it, a tingling sensation can be felt in the finger tips if the sound is projected against them. This upper limit of audibility known as the *threshold of feeling* is almost as well defined as the lower limit or *threshold of audibility*. These facts are illustrated in fig. 107.

To get this figure, the pressure amplitude (strictly speaking the root mean square amplitude in dynes per square centimetre) is plotted on a logarithmic scale as ordinates; the logarithmic scale is chosen partly as being more suitable for showing the graph, and partly because uniform increments of pressure-amplitude on this scale correspond fairly closely to equal increments in the sensation of loudness. The frequency is plotted, also on a logarithmic scale, as abscissæ. The dotted portions of the curves enclosing the area are more or less conjectural, as insufficient work has been done in these regions to determine the curve accurately. The two dotted lines on either side of the main boundary lines show the probable deviation of an observation

made upon one particular person, it being found that individual ears differ very greatly, and that only by taking the mean of a large number of sets of observations can a smooth curve be obtained. The curves show that the ear is most sensitive in the neighbourhood of the frequency 2048, and that here a pressure amplitude considerably less than one-thousandth of a dyne per square centimetre is audible. It

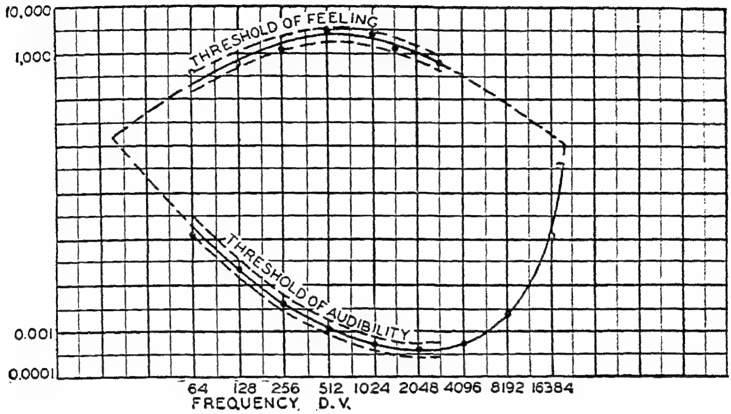


Fig. 107.—Sound sensation area showing frequency plotted logarithmically, the numbers corresponding to cycles per second, and root mean square pressure amplitudes plotted logarithmically, the numbers giving dynes per square centimetre.

will also be seen from the diagram that when the pressure amplitude is one-tenth of a dyne per square centimetre, the limits of audible pitch are given by the frequencies 64 and 16,384, whereas if the loudness corresponding to ten dynes per square centimetre pressure-amplitude is used the limits are about 23 and 20,000 respectively. The area of the enclosed space is a measure of the number of pure tones differing in pitch and loudness which the normal ear can hear, and this is found to be about 300,000.

Deafness.

Audiometers for testing abnormal hearing are now available, which enable us to ascertain the smallest loudness required to excite a sensation of hearing for tones of different pitch, and from these observations graphs can be drawn representing the behaviour of abnormal ears. The extent of the sensation area for a deaf person as compared with that of the normal ear gives us a good method of estimating percentage deafness. Fig. 108 gives some actual cases investigated by Fletcher, while fig. 109 gives an audiogram for a deaf person, plotted in a slightly different way. In fig. 108 the units chosen are different, but the method of plotting is the same. The shaded area represents the loss of hearing as against the normal ear. In the case

of A the hearing is actually a little more acute than normal about the middle of the pitch region, and the deafness is mainly for relatively high-pitched notes. In the case of B the deafness is mainly in the

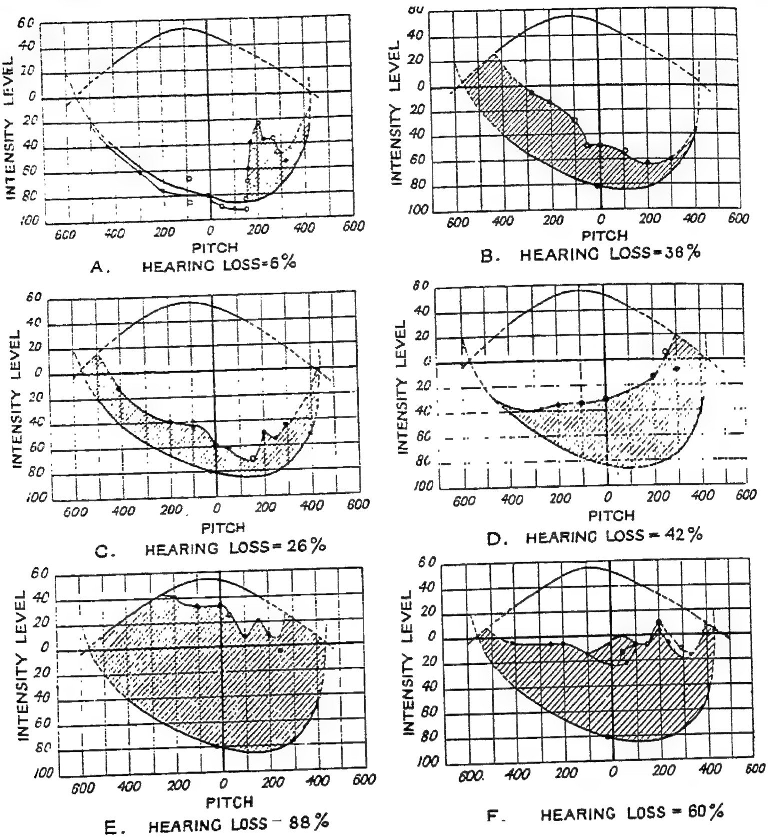


Fig. 108.—Audiograms for typical cases of Deafness

The whole area enclosed represents the sensation area for a normal ear, the shaded portion represents the insensitive region for the ear examined. A shows hearing loss for high notes with slightly increased intensity for notes of low and middle pitch. B shows hearing loss mainly for low notes. E shows nearly total loss of hearing. The units on the vertical scale are decibels of loudness above or below the loudness corresponding to maximum range of pitch. The units on the horizontal scale are centi-octaves of pitch above and below a frequency of 1000. 1 centi-octave = 12 cents = 3 savarts (approx.).

lower ranges of pitch, while E shows a pretty general loss of hearing and is only sensitive to very loud tones in the middle region of pitch.

It is remarkable that the pressure-amplitude required to excite the sensation of hearing may be 1000 times greater than that for the normal ear, without the person in question being more than very

slightly deaf; while even if the pressure amplitude required is 10,000 times that for the normal ear, the person is still able to follow ordinary conversation. When it becomes as great as 100,000, apparatus of some kind is required, while at something over 1,000,000 the threshold of feeling is reached and deafness is complete.

It may be useful here to call attention to work recently published in connexion with the possibility of teaching deaf people to perceive sounds by the sense of touch. The vibrations of a diaphragm can be felt in the finger tips, and attempts have been made by receiving

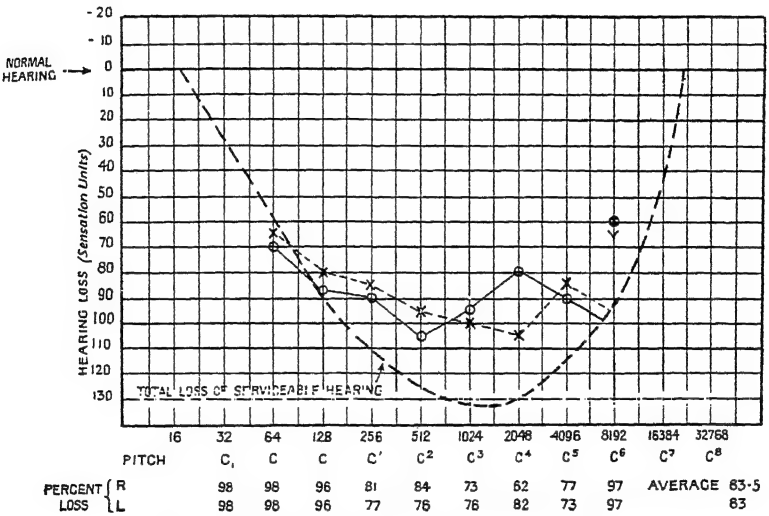


Fig. 109.—An audiogram plotted from audiometric records

sounds in a microphone and transmitting them amplified to a diaphragm to enable deaf people to understand speech. In its more recent forms the apparatus has been arranged so as to carry vibrations to the thumb and four fingers, each digit being made responsible for a certain range of frequencies. This is analogous to the distribution of frequencies over the basilar membrane of the ear. It is claimed that after some training the subjects are able to detect frequencies from 150 to 2700 and amplitudes varying from ·00125 to ·000125 cm., and that conversation can be followed and understood. The ear is, no doubt, a highly specialized development of the tactile sense, and this may be regarded as a return to a primitive form of ear.

Noise.

A word on the general subject of noise may not here be out of place. The ear is continually in receipt of the pressure disturbances

associated with sounds. Closing the eyelids rests the eye, the stimuli of the light being no longer received on the retina, and during the hours of sleep the eye gets this relief. But the ear has no convenient flaps which can cut out sound, and even while we are unconscious of them the stimuli of noise are continually at work. We may suppress sounds from our consciousness but they are active all the time, and the fact that we can hear a clock stop makes it clear that we have to make some readjustment to the new conditions. Even during sleep sounds are making their impression on us. If they are familiar we may be unconscious of them or fit them into our dreams, but if they carry a meaning for us we awake to them at once. A mother may sleep through a considerable amount of general noise, but be awake in a moment at the least sound from her child.

The harmful effects of noise are two-fold. Intense noise may produce actual injury, as in the case of boilermakers' deafness. On the other hand, continuous noise or intermittent noise may produce irritation and fatigue. It is well known that noise which may be completely ignored when we are fresh and in good health, becomes almost intolerable when we are tired and our physical or nervous tone impaired. This fatigue produced by noise is a subject which deserves more consideration than it has yet had. Investigation of office noises, where a large number of typewriters are at work and no precautions for the reduction of noise are taken, indicates that the output is diminished and the fatigue increased in a very marked degree. An important paper has been published by the International Labour Office of the League of Nations, in which the whole subject is discussed in detail in relation to occupations and its importance emphasized. It is claimed in this paper that noise, even though of slight intensity, may diminish output to a figure as low as 40 per cent of the normal.

Acoustics of Buildings.

This brings us naturally to the subject of suppression of noise in rooms, and to that no less important subject, the acoustics of buildings. For centuries the cause of bad acoustics in churches and halls was regarded as a mystery to be dealt with only by wires stretched across the roof or by other methods of black magic. Thanks to the work of the late Professor Sabine of Harvard University the dark mystery has been dispelled, and we are now in a position not only to understand the problem but to solve it. Defective acoustics has, in the majority of cases, a very simple origin. Any sound produced in a building lasts too long after its production; it goes echoing or reverberating round the building while other sounds are being produced, and this makes it impossible for the hearer to pick out the various sounds in their proper order and discriminate between them. Thus if a sound lasts for 3 sec., and if a speaker speaks at the rate of three syllables a second, the

sound waves corresponding to nine syllables will all exist in the room at any moment together, and will produce a confusion which will make it impossible for the listener to interpret the speaker. Faced with conditions like these, the speaker's only chance is to speak very deliberately and not too loudly. His temptation on the other hand is to speak more loudly and so make the confusion worse confounded. It has often been remarked that the acoustics of the Greek and Roman theatres were admirable. There are several reasons for this, not the least important of which is the fact that they have no roofs. To cure defective acoustics a simple remedy is always at hand: the removal of the roof of a building will almost certainly cure the acoustic defect. This solution, however, has, in a climate like ours, some obvious disadvantages, and we are constrained to pursue our investigations in other directions. Stated in scientific terms, the problem simply amounts to saying that if you have a "source" of energy in a closed space you must also supply a "sink", that is to say, some way to get rid of the energy when it has performed its task. Hard walls, ceilings, and floors reflect so much of the sound energy and absorb so little that they contribute only slightly to the absorption required. On the other hand, soft porous materials like carpets, curtains, upholstered chairs, and so on absorb strongly, the air being driven in and out of the pores of the material by the compressions and rarefactions of the sound waves, and the energy of the sound wave being thereby dissipated as heat. The different effects due to reverberation are familiar to singers who have rehearsed in an empty hall, and to all of us who have spoken in our own rooms when the carpets are up and the furniture removed during a spring-cleaning.

Reverberation.

The whole matter was first put on a scientific basis by Sabine of Harvard in the course of experiments designed to effect the cure of a lecture-room at that university. Having decided in his own mind that excessive reverberation was the trouble, he took an organ pipe as source of sound and measured by ear with a stop-watch the *time of reverberation*, i.e. the duration of audible sound after the source had been stopped. This method was afterwards improved by recording electrically the instant at which the air blast to the pipe was stopped and the instant at which the sound ceased to be audible. Introducing cushions from a neighbouring lecture theatre, he found that the time of reverberation was reduced, and that, assuming the surface in the empty room to be equivalent in power of absorption to a certain area of cushion, then the time of reverberation was strictly inversely proportional to the total area of cushion surface in the room. In this way, i.e. by introduction of cushions, it was obviously possible to give the time of reverberation any desired value. For this particular room

then, the problem may be regarded as solved if we know what time of reverberation to aim at.

The solution, however, is open to several grave objections. In the first place it is obtained in terms of cushions. Now the primary purpose of cushions is that they should be sat upon, and they cannot, in this case, be used as absorbers. In the second place it leaves out of account the difference made by the audience, which every speaker and singer knows to be very important, and in the third place it suggests no way of designing a building so that it shall be satisfactory and stand in no need of subsequent acoustic correction.

Sound Absorbents.

With regard to the first difficulty, the obvious way out is to express the absorbing power of cushions and all other materials in terms of some standard unit which shall be invariable and easily accessible for all experimenters. Sabine deserves great credit for the simplicity of the standard chosen. All the sound which falls on an open window

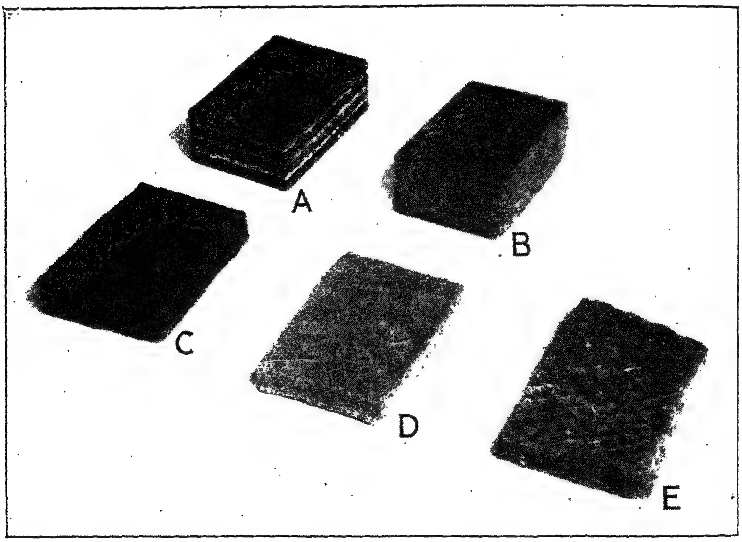


Fig. 110.—A and B, Vibration-absorbing combinations of cork and felt. C and D, Good quality felts suitable for sound absorption. E, Builder's felt.

passes out and none is reflected. The open window may therefore be treated as a complete absorber. Ideally it is possible to find directly how many square feet of a given material produce the same change in the time of reverberation as so many square feet of open window. When this has been done we have found what may be called the *coefficient of absorption* of the material. Thus, if 100 sq. ft. of hair felt

reduce the time of reverberation in a room by the same amount as 60 sq. ft. of open window, we may say that the coefficient of absorption of hair felt is 60/100 or ·6, and multiplying the area of hair felt introduced into any room by ·6 we get the total absorption in terms of the

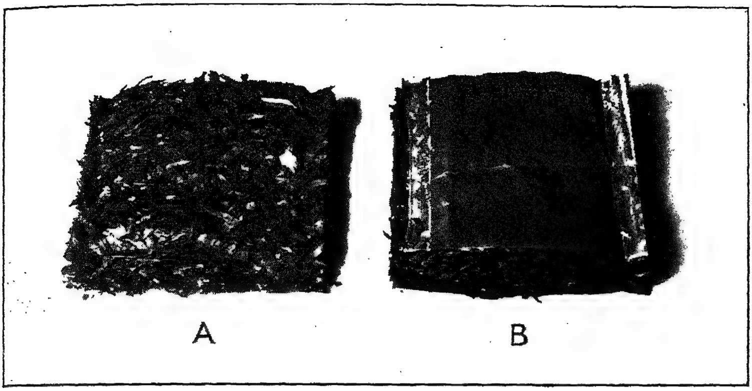


Fig. 111.—A, Cabot quilt with paper envelope removed. B, Cabot quilt as commercially available

open-window unit. Other and more convenient methods of measuring this coefficient of absorption have been devised, but this direct method makes the real nature of the measurement clear.

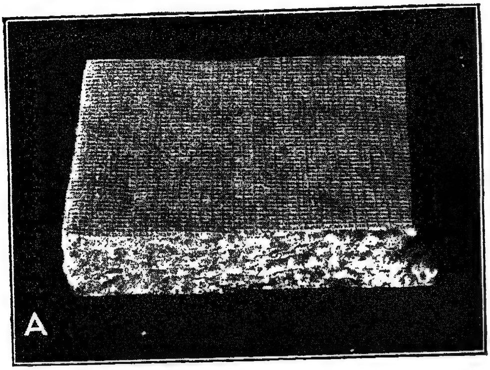
In the following table the coefficients of absorption of a large number of familiar materials are given, and the table enables us to calculate the total absorbing power of any given hall or church.

ABSORPTION COEFFICIENTS

(Measured for sound of frequency 512)

Ordinary Materials	
Brick wall (unpainted)	0·031
Brick wall (painted)	0·017
Wood sheathing	0·10
Cushions	0·54–0·76
Plaster (gypsum on hollow tile)	0·020
Plaster (lime on wood lath)	0·034
Plaster (lime on wood lath with finishing coat)	0·018
Tiles	0·029–0·053
Audience (per person)	4·7
Special Absorbents	
Slagbestos	0·65
Cabot quilt suitably mounted	0·74
Hair felt suitably mounted	0·41
Celotex panelling	0·19
Sabine plaster	0·23–0·29
Akoustolith tiles	0·19

It will be noticed that ordinary building materials show a very low coefficient of absorption. In the case of plaster (gypsum on hollow . 50 sq. ft. are required to produce the same absorption as 1 sq. ft. of open window. As a single member of the audience gives an absorption equal to 4·7 sq. ft. of open window, it follows that one person provides as much absorption as 235 sq. ft. of plaster. This shows how valuable the audience is from the point of view of absorption.



ig. 112.—Balsam Wool with Covering Felt

Some special absorbents are shown in figs. 110, 111, 112, and 113. In fig. 110, A and B are laminated combinations of felt and cork, specially designed for preventing sound from spreading from room to room through a building, and can be interposed between girders, cross

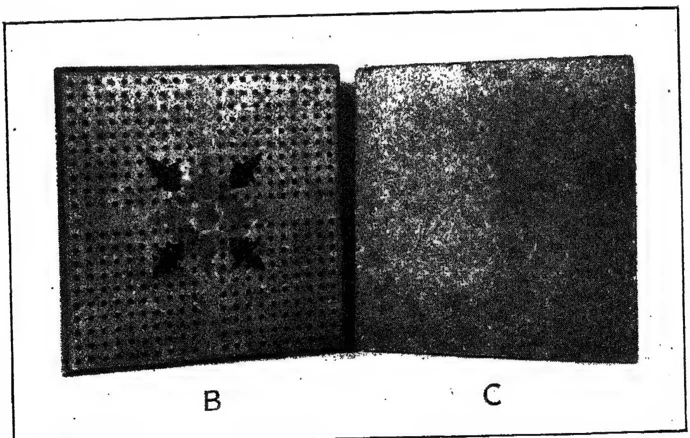


Fig. 113.—B, Acousti-celotex showing perforations and decorative effect. C, Celotex

beams, &c. C and D are felts which can be applied to the walls of a room, preferably mounted so as to leave an inch or two between the felt and the wall, and are usually covered with canvas or some other suitable material. In fig. 111 is shown a good non-inflammable material consisting of loosely packed sea-weed enclosed and quilted in a paper

envelope. It is used in the same way as the felt. Fig. 112 shows a balsam wool and fig. 113 a material known as Celotex. This is a waterproofed cane-fibre board which, especially in its perforated form, has a comparatively high absorbent value. All these materials may be used for correction, but if a building is well planned no correction should be necessary. The special plaster shown in the table can be used instead of ordinary plaster, and has a coefficient of absorption ten to fifteen times as great, while the special tile has a coefficient of absorption four to six times as high as that of the ordinary tile.

Sabine's Formula.

The area of each material present in walls, floor, and ceiling must be measured, and this area multiplied by the appropriate coefficient of absorption. Adding all these products together, we shall have the total absorbing power of the room.

We have now the relation:

$$\mathrm{A} \times t = k$$

for any particular room, where A is the total absorbing power, t is the time of reverberation, and k is a constant for the particular room. We must next note that the time of reverberation will obviously depend on the loudness of the source, so it is necessary to have a source of standard loudness. Sabine found that the intensity of his source was approximately a million times the minimum audible intensity, and this has therefore been accepted as the standard value. As A and t are both easily measurable by the methods already suggested, we can calculate k for any particular case. Sabine did this for a number of rooms of very different sizes, and found that k was proportional to the volume of the room. If then k is the constant for a particular room and V the volume of the room, we shall have:

$$\frac{k}{\mathrm{V}} = \mathrm{K},$$

where K is now a constant applicable to all rooms. Dividing both sides of the equation shown above by V, we have:

$$\frac{\mathrm{A} \times t}{\mathrm{V}} = \frac{k}{\mathrm{V}} = \mathrm{K},$$

$$\text{or} \qquad t = \frac{\mathrm{K} \times \mathrm{V}}{\mathrm{A}}.$$

K is found to have the value ·05 when measurements are made in feet. This means that when a source of standard intensity is sounded in a room, the time of reverberation is given by the volume of the room multiplied by ·05 and divided by the absorbing power measured in the way indicated above. This very simple relationship is the

basis of the whole science of the acoustics of buildings in so far as it is concerned with reverberation, and something like 90 per cent of its problems are reverberation problems. If measurements are made in metres instead of feet, the constant becomes ·162 instead of ·05, but the formula otherwise remains unchanged.

We now have to deal with the question of the audience. Every speaker knows that however uncertain the intellectual absorption of his audience may be, its physical absorption is very marked. It is very much easier to speak in a full hall than in an empty one, and the difference is not merely psychological. The absorbing power of an audience has been determined by exactly the method outlined earlier in this lecture, and the not very flattering result arrived at that a single auditor is equivalent to about 4·7 sq. ft. of open window. This means that to get the absorption due to an audience we must multiply the number of persons by 4·7. It is interesting to note that Sabine found a woman to be slightly more absorbing as a member of an audience than a man, but the difference is very slight, and as this kind of absorption is purely superficial it must be attributed entirely to dress. It was unkind of a prominent physicist to suggest that it was an instance of the general rule that good radiators are good absorbers.

Appropriate Values for the Time of Reverberation.

Since we are now in a position to calculate the time of reverberation for any building which is found to be unsatisfactory, and to suggest a method of adjusting the time of reverberation t to any required value, the next important step is to ascertain if possible what value of t we are to aim at. This question has been approached by two different methods. The first method was adopted by Sabine when consulted about the erection of a new concert-room at Boston. A large number of concert-rooms on the Continent of Europe were visited, their merits appraised by musical experts, and their times of reverberation determined. In this case the Leipzig Gewandhaus was judged to be the best from the point of view of the performance of music, with a time of reverberation when full of 2·3 sec.

Another method was adopted by Sabine in which, taking a series of rooms, he arranged for the adjustment of each by the introduction or removal of absorbents to what was regarded by musical experts as exactly right for the performance of pianoforte music. The results of this experiment are summarized in the table below, and show how extraordinarily accurate musical taste is in this matter, the preferred value for t being in each case about 1 sec.

Watson has summarized data for a number of auditoria, drawing a distinction between those used for music only and those used both for music and for speech. It shows, as might be expected (figs. 114 and 115), that the preferred value varies with the purpose for which

Room Number.	Volume.	Absorbing Power of Room.	Gentlemen Present.	Absorbing Power of Clothing.	Number of Metres of Cushions.	Absorbing Power of Cushions.	Total Absorbing Power.	Reverberation in Seconds.	Remarks.
1	74	5·0	0	0	0	0	5·0	2·43	Reverberation too great
		5·0	5	2·4	0	0	7·4	1·64	Reverberation too great
		5·0	5	2·4	13	12·8	20·2	0·60	Reverberation too little
		5·0	5	2·4	11	10·1	17·5	0·70	Better
		5·0	5	2·4	8	7·3	14·7	0·83	Better
		5·0	5	2·4	6	5·5	12·9	0·95	Condition approved
		5·0	5	2·4	4	3·6	11·0	1·22	Reverberation too great
2	91	6·3	0	0	0	0	6·3	2·39	Reverberation too great
		6·3	6	2·9	0	0	9·2	1·95	Reverberation too great
		6·3	6	2·9	7	6·4	15·6	0·95	Reverberation too little
		6·3	6	2·9	5	4·6	13·8	1·10	Condition approved
3	210	14·0	0	0	0	0	14·0	2·46	Reverberation too great
		14·0	7	3·4	0	0	17·4	2·00	Reverberation too great
		14·0	7	3·4	12	11·0	28·4	1·21	Better
		14·0	7	3·4	15	13·7	31·1	1·10	Condition approved
4	133	8·3	0	0	0	0	8·3	2·65	Reverberation too great
		8·3	7	3·4	0	0	11·7	1·87	Reverberation too great
		8·3	7	3·4	6	5·5	17·2	1·26	Better
		8·3	7	3·4	10	9·1	20·8	1·09	Condition approved
5	96	7·0	0	0	0	0	7·0	2·24	Reverberation too great
		7·0	4	1·9	0	0	8·9	1·76	Reverberation too great
		7·0	4	1·9	10	9·1	18·0	0·87	Reverberation too little
		7·0	4	1·9	8	7·3	16·2	0·98	Better
		7·0	4	1·9	5	4·6	13·5	1·16	Condition approved

the hall is to be used, and to some extent with the size of the hall.

One might reasonably suppose that a speaker would prefer an entire absence of reverberation, but this is not so. Some years ago *Punch* published an article in which it was suggested that many people furnish their drawing-rooms as they ought to furnish their bath-rooms and vice versa. It was pointed out that we never feel more inclined to vocal exercise than in a bath and never less than in a drawing-room. There was a considerable amount of sound sense behind the fun of this article. The comparatively long time of reverberation due to the lack of absorbing materials in a bath-room gives us a sense of power, while the carpets and heavily upholstered furniture of many a drawing-room reduce the time of reverberation to a value at which we cease to be stimulated to vocal activity.

Absence of reverberation is the condition which the open-air speaker has to face, and when obtaining in a room it gives rise to the complaint that the room is *dead*. A speaker likes a certain amount of

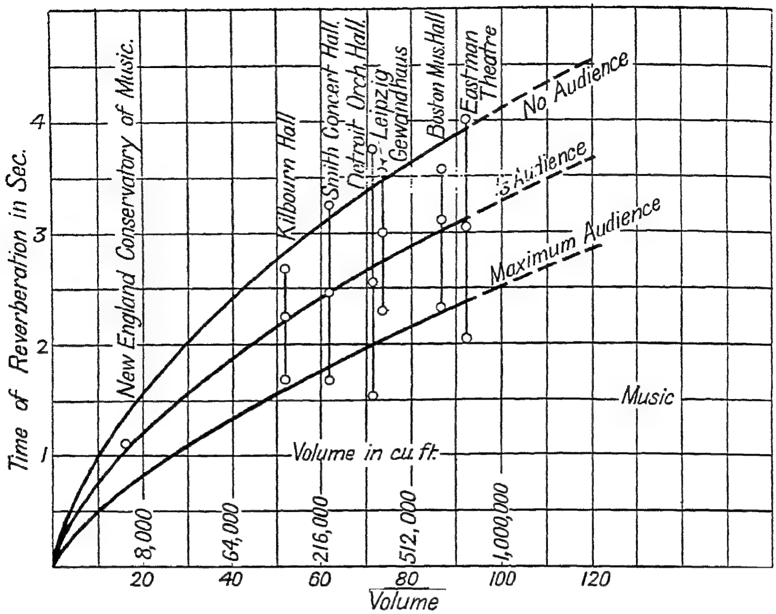


Fig. 114.—Preferred time of reverberation for concert halls of different volume

Taking the cube root of the volume for any hall in which we are interested, we can read off from the graph the preferred value of the time of reverberation.

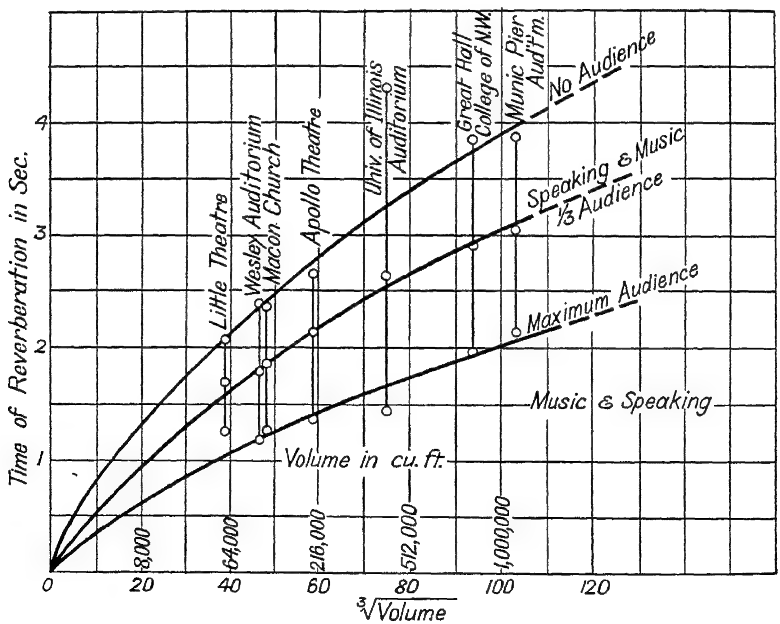


Fig. 115.—Preferred time of reverberation for auditoriums used both for speech and music

"response" from the room, and this is supplied in rooms of moderate size by a time of reverberation of 1 sec. On the other hand, while this is not bad for chamber music, singers and instrumentalists prefer a little more reverberation, while for choral and organ music, especially that which depends for its effects on massiveness rather than on detail, a considerably increased time of reverberation up to 2·3 or 2·5 sec., or even longer, may be desirable.

Broadly speaking we may say that if a building is to be used for a single purpose, as for instance a council chamber or concert-room, we can say very accurately what time of reverberation it ought to have. If it is to be used for a variety of purposes we can arrange a compromise which, though not ideal, will give no reasonable ground for complaint. In cases where a building is seriously defective, the time of reverberation is usually much greater than any of the figures here suggested.

Acoustic Correction of Buildings.

As an example of the correction of excessive reverberation we may take the case of the Examination Hall of Cambridge University, for which figures have been supplied to me by Mr. Hope Bagenal, A.R.I.B.A., under whose direction the work was carried out.

EXAMINATION HALL, CAMBRIDGE

Reverberation before correction

Absorbent.	Remarks.	Area (sq. ft.) or Number.	Coefficient.	Units of Absorption.	Adjustment.	Net No. of Units of Absorption.
Hard plaster ceiling and part walls	Lime plaster distempered	10,400	0·025	260	—	260
Glass	—	1,260	0·027	34	—	34
Wood panelling	Oil painted	3,370	0·06	202	—	202
Floor	Cork	5,400	0·04	216	Less 10% for shading	195
Wood chairs	—	1,000	0·1 per chair	100	—	100
			Total Permanent Absorption ..			791
Full audience	On wood chairs	1,000	4·7 less 0·1 = 4·6 per person	4600	—	4600
Half audience	Ditto.	500	Ditto.	2300	—	2300

The above table indicates how the absorption of the various surfaces was calculated. The first two columns give the nature of the

surface; the third column gives the area in square feet in the case of surfaces or the number in the case of chairs or persons; column 4 gives the coefficient of absorption; column 5 is the product of 3 and 4 and gives the number of units of absorption. Column 6 contains any reason for adjusting the figures in column 5, while column 7 gives the net value. It will be noted that, allowing 10 per cent for the shading of the floor by chairs, &c., the total permanent absorption is 791 units. The effect of the audience is shown in the last two lines of the table. The coefficient of absorption is 4·7 per person, but each person occupies a chair and prevents it from acting as an absorbent, so that the net increase of absorption is 4·6 units per person. The volume of the hall is 161,000 c. ft., and if we calculate t, the time of reverberation, for full audience and half audience from the simple formula already given,

$$t = 0{\cdot}05\frac{V}{A},$$

we get

t for full audience	1·5 sec.;
t for half audience	2·6 sec.

Thus the time of reverberation is satisfactory for a full audience but excessive for a half audience, and this accounted for the numerous complaints received when the hall was used as a lecture-room, especially with small audiences.

A wall treatment was recommended rather than a ceiling treatment for reasons of cost. The maximum wall area above the wood panelling of the room amounted to 2040 sq. ft., and on this was placed, in the form of large panels, two layers of triple-ply Cabot quilt, screened with canvas and distempered. The treatment is practically invisible, and the above table has now to be modified as follows:

Hard Plaster	10,400 less 2,040 = 8,360 sq. ft.	0·025	209 units
Triple-ply quilt, two layers	2,040 sq. ft.	0·7	1428 units
Remainder as in above table			531 units
Total Permanent Absorption			2168 units

t for full audience ..	1·2 sec.;
t for half audience ..	1·8 sec.

This gives very good audibility with a full audience and a very marked improvement for smaller audiences.

Acoustic Design.

It will be fairly obvious that these calculations can be made as easily before the building is put up as afterwards, and that therefore the necessary correction can be done in advance and not as an afterthought. The case of the White Rock Pavilion at Hastings, designed as a music-room, will illustrate this point, and here again I am indebted for the figures to Mr. Hope Bagenal, who was consulted by the architects, C. C. Voysey and the late H. P. Morgan. The table on p. 124 illustrates how the calculation was made, and calls for no further comment except that it should be noted that the seats are upholstered, and therefore supply a considerable amount of absorption even when the room is empty. They reduce the effective absorption of the audience from 4·7 units per person to 3. The pavilion has earned the cordial approval of those who are best able to judge.

It will be noticed that the volume per seat of audience is 200 c. ft. This is a useful rough guide to the architect. A concert hall with less volume per seat will tend to be "dead", especially if small.

It only remains to add that Sabine's theory and its later developments have been triumphantly vindicated in their practical application to a large number of problems, both in cure and in design. There is now not the slightest excuse for the production of an unsatisfactory building, either from the point of view of music or of speech; but we shall never get the universal application of these principles and the entire disappearance of the unsatisfactory building until the general public realizes that acoustic defect in a new building is a sin against the light, that the acoustics of buildings is a science, and that the architect, if he is made responsible, is just as much to be blamed for acoustic defect as for defect in lighting, heating, or ventilation. In defence of the architect it must, however, be said that his designs are apt to be considered by his employers purely on their artistic merits and he gets very little encouragement to plan for good acoustics.

We may return now to a consideration of the suppression of noise, and it is obvious that a reasonable use of absorbents is very much to be desired in noisy rooms. The Cabot quilting referred to earlier has been used with great success in a number of noisy offices, with increased comfort to the staff and increased efficiency of working. In the head office of the Midland Bank a room containing a personnel of about 100, with some eighty adding machines and typewriters, was treated in this way. The result was so satisfactory that the ceilings of the whole building have been similarly treated. This treatment of the ceiling of a room with Cabot's quilt is also very effective in the diminution of noise due to traffic, when windows facing on to a main thoroughfare have to be open at the top for ventilation.

WHITE ROCK PAVILION, HASTINGS

Reverberation Table

Description of Absorbent.	Remarks.	Area or Number.	Co-efficient.	Number of Units.	Adjustment.	Net Number of Units.
Plaster: hard ..	Keens or fibrous	22,500 sq. ft.	0·02	450	—	450
Wood: platform floor and staging	Oak	11·75 sq. ft.	0·06	70·5	Less 10 per cent for shading by players	63
Wood: panelling round orchestra	Oak, ½-in. 5-ply panels; 2-in. air-space	526 sq. ft.	0·1	52·6	—	52·6
Wood: doors ..	Oak, 2 in.	774 sq. ft.	0·06	46·4	—	46·4
Glass: laylight and windows	—	224 sq. ft.	0·027	6	—	6
Carpet area on ground floor promenades	Five - frame Wilton on thick under mat	9690 sq. ft.	0·25	2400	Less 10 per cent for shading by seats, &c.	2160
Curtains	Thin	224 sq. ft.	0·15	33	—	33
Vents	—	100 sq. ft.	0·5	50	—	50
Upholstered seat; arms not upholstered	"Goat hair"	1400	1·7 per seat	2380	—	2380
Settees, large up-upholstered	Seating each 5 people	15	20 units each settee	300	—	300
Performers: average number on platform	Seated on wooden chairs	40	4·7	188	—	188
			Total Absorption		.. ..	5729
Audience full ..	Take co-efficient at	1400	3·0	4200	—	4200
Audience one-third	4·7 − 1·7 = 3·0	466	3·0	1398	—	1398

Volume = 280,000 c. ft.;
Volume per seat of audience = 200 c. ft.

$$\text{Then (for full audience) } t = \frac{V}{A} \times 0{\cdot}05$$

$$= \frac{280{,}000 \times 0{\cdot}05}{5729 + 4200}$$

$$= 1{\cdot}4 \text{ sec.}$$

For one-third audience $t = 2$ sec.
When the Pavilion is empty $t = 2{\cdot}4$ sec.

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LECTURE VI

How Sounds are Recorded and Reproduced

Early Methods of Recording and Reproducing.

In the previous lectures we have already discussed methods of recording sounds, but these methods have not been available for the reproduction of sound from the record. It is obvious that our field for the enjoyment of speech and music is enormously widened if these can be recorded, stored, and reproduced at will. This is now accomplished by means of the gramophone record and the talking film, and

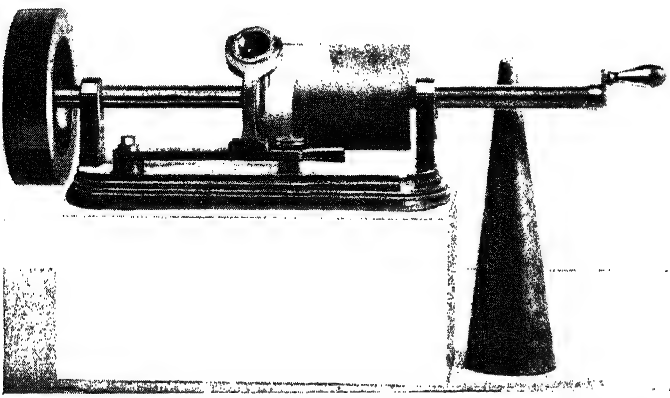


Fig. 116.—Early type of Edison machine for recording and reproducing: in collection of Royal Institution

we shall consider some of the methods by which success in this field has been achieved.

In 1877 Edison was successful in producing a record of this type on tin-foil and waxed paper. His apparatus is shown in fig. 116, and consists essentially of a membrane with stylus attached which receives the sounds and produces an indented record on tin-foil, this tin-foil being wrapped round a cylinder which can be rotated and moved parallel to its axis by a screw. A spiral line of varying depth is thus traced on the recording material, and after the record is made the

point of the stylus is again placed at the commencement of the record and the motion of the cylinder repeated. The stylus thus retraces the groove, and the variations in depth cause it, and therefore the attached membrane, to reproduce their original motion, and so to generate in the air changes of pressure similar to those in the original sound wave. It need hardly be said that the reproduction is very difficult and very imperfect. The process was improved by Bell, who used cylinders of wax and separate machines for recording and reproducing. The re-

Fig. 117.—Berliner's Gramophone, 1894

cording stylus was sharp and fixed on a stiff membrane, while the reproducing stylus was rounded and attached to a loose membrane. Further improvements were introduced by Edison, who produced a commercial type of machine. He obtained long records by using a very fine pitched screw, and duplicated the records by an electrotype process which is still part of the process of manufacturing gramophone records.

In 1894 there was produced the Berliner machine (fig. 117), which showed several new features characteristic of the later types. The record was made on a disc, and the vibrations of the recording stylus were from side to side instead of up and down. The record thus consisted of a wavy spiral groove on a disc instead of a spiral groove of

varying depth on a cylinder. The machine was hand-driven, and the reproducing diaphragm was fitted to a short conical horn, the function of which was not at all clearly understood. In 1899 there appeared a new model (fig. 118) driven by clockwork, and immortalized by Francis

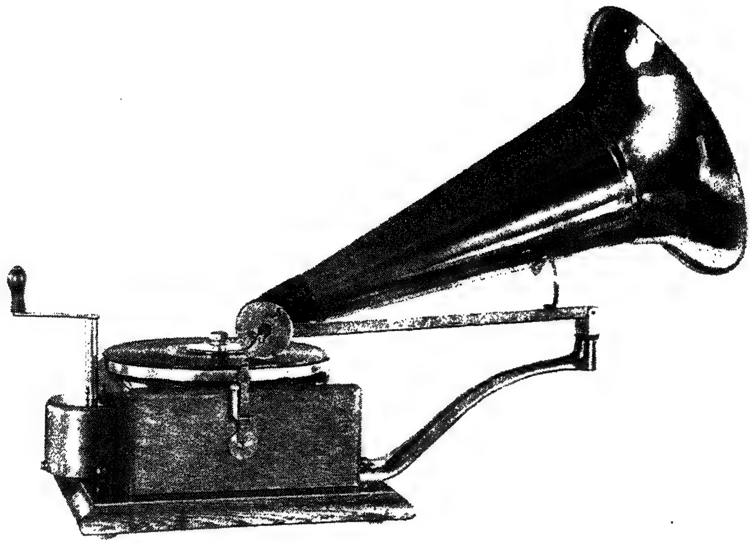


Fig. 118.—H.M.V. Dog Model, 1899

Barraud in the famous picture which has been adopted by the Gramophone Company as its trade-mark. No more interesting commentary on the development of the gramophone is possible than a comparison of the reproduction even of a modern record by this Dog Model and by one of the latest models now in use.

Linking of Sound Waves and Electrical Waves.

Before we can discuss the improvements in technique which have made the enormous advance possible, we must consider some of the ways in which sound waves can be transformed into electrical waves and vice versa. It is a well-known fact that the electrical resistance across the point of contact between two lumps of carbon varies very greatly with the pressure applied. Variable electrical resistances are made, which consist of a series of plates of carbon to which a variable pressure can be applied by means of a screw. If a resistance of this kind is inserted into an electrical circuit, with a galvanometer or other method of indicating the current flowing, every variation in the pres-

sure applied shows itself at once as a change in the electric current in the circuit. This is the principle of the ordinary telephone transmitter (fig. 119) into which we speak. The pressure waves entering the mouthpiece of the telephone impinge on a plate separated from another plate

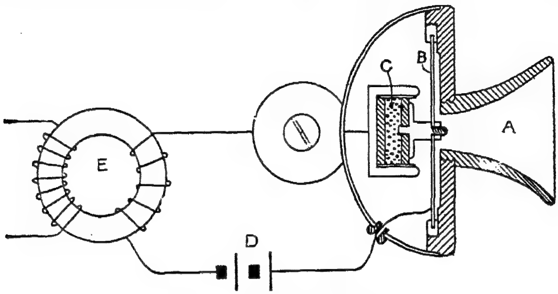


Fig. 119.—Carbon Transmitter

A, mouthpiece; B, diaphragm; C, carbon granules subjected to varying pressure by the movements of the diaphragm; D, battery sending current through the granules; E, transformer.

by a loose contact. The movement of the front plate alters the pressure on the contact, and so the resistance between the plates. This resistance is part of a circuit in which the variations of current reproduce, therefore, the varying pressures of the sound waves due to the voice.

Another common method of linking sound waves and varying electric current is the method applied in the telephone receiver (fig. 120). Here we have a thin magnetic diaphragm placed in front of the end of a magnet. The magnet is surrounded by a coil of wire. Any movement of the magnetic diaphragm causes changes in the strength of the field magnet, and any change in the strength of the field magnet induces a current in the coil of wire surrounding it. This principle was originally applied by Bell, both to the telephone transmitter and to the receiver. The pressure waves due to the voice caused the diaphragm to vibrate. These vibrations caused a varying current in the coil surrounding the field magnet; this coil was in series with an exactly similar coil which formed part of an exactly similar arrangement at the other end of the telephone line. The variations in the current in this second coil caused variations in the strength of the field magnet, and these in turn caused

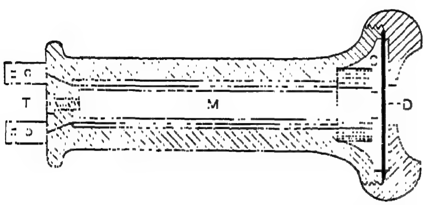


Fig. 120.—Electromagnetic Transmitter or Receiver

D, Magnetic diaphragm vibrating close to one end of a magnet M. C, coil surrounding end of magnet. Vibrations of D cause changes in magnetization of M and this induces a varying current in the coil which is led off through the terminals T.

variations in the force of attraction of the field magnet on the diaphragm. Thus the diaphragm at the receiving end reproduces the movement of the diaphragm at the transmitting end, and so reproduces the sounds which were the original source of the whole series of phenomena.

These two methods of linking mechanical vibration to varying electric current are illustrated in the apparatus here shown (fig. 121). A bar of soft iron has wound round it a coil of wire which forms part of a circuit containing a variable carbon resistance and a battery. In front of the bar is suspended a thin iron sheet. Every alteration of

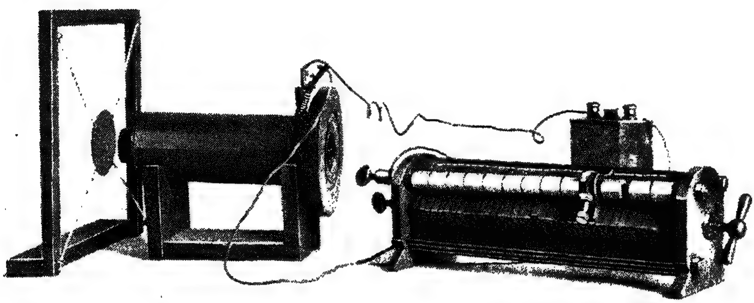


Fig. 121.—Model illustrating telephone transmitter and receiver

The resistance of the circuit of the electromagnet is varied by varying the pressure applied by a screw to a series of carbon plates. A magnetized disc is suspended in front of the electromagnet.

pressure applied to the carbon resistance is indicated by a movement of the iron diaphragm. The carbon resistance represents the transmitter of a telephone, and the iron bar and diaphragm the receiver.

The third method of linking is that known as the moving coil. Instead of the iron diaphragm of the preceding experiment, we may use a suspended coil. Now a coil carrying an electric current is attracted by a magnet in exactly the same way as a magnetic disc, and the attraction will depend on the strength of the current and the number of turns in the coil. If, therefore, a variable current is passed through the coil it will be subject to a varying attraction by the magnet, and will move in a way which corresponds exactly to the changes in current through it. If the coil is attached to a diaphragm, then the diaphragm will vibrate with the movement of the coil, and variations in the electric current through the coil will be transformed into the motion of the diaphragm, and therefore into the variable air pressure which constitutes sound. This is, in effect, the principle of the moving-

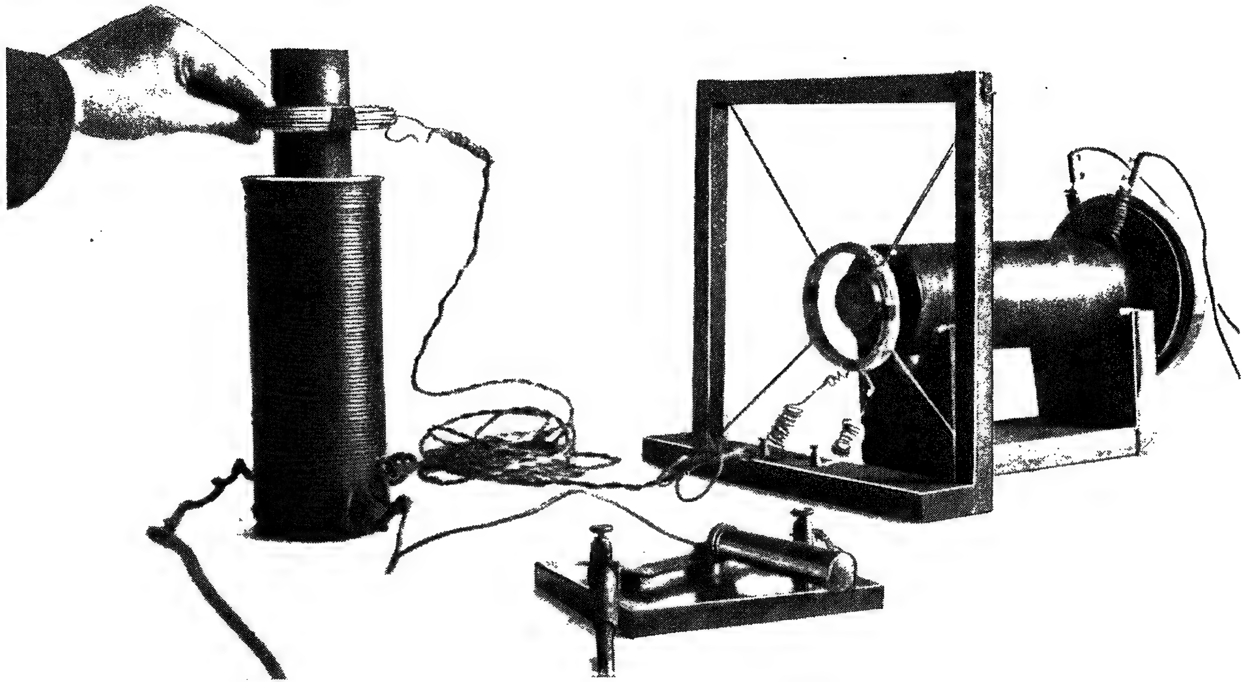


Fig. 122.—Moving coil method of linking vibrations

A movement of the coil held in the hand induces a current in its circuit which includes the second coil suspended in front of a magnet

coil loud-speaker. On the other hand, if the coil be moved to and fro in the neighbourhood of the magnet, a varying current is induced in it, so that we could design a telephone system in which coils were substituted for the magnetic diaphragm previously indicated. This is illustrated by the experiment shown in fig. 122, where we have two coils in the neighbourhood of two magnets, one of them being suspended. When one coil is moved in the neighbourhood of its field magnet, a varying electric current is induced which flows round the other coil and causes it to oscillate to and fro in a way which reproduces the movement of the first coil.

There are many other methods of linking sound waves and current waves, but one more must suffice. If we have two parallel plates, one of which is connected to earth and the other insulated, they form an electrical condenser. If now a fixed charge is given to the insulated plate it will be raised to a definite potential. If this plate is now moved nearer to the earthed plate, the capacity of the condenser is increased and the potential of the insulated plate falls. If the distance is increased the capacity is diminished and the potential rises. Thus the movement of either plate causes a corresponding change in potential. This is the principle of the condenser transmitter (fig. 123) widely used in broadcasting. The pressure waves due to the voice impinge on a very flexible plate, which is one of the plates of a condenser with a very small air space. The movement of this plate varies the capacity of the condenser and so the potential of the insulated plate. This variation of potential can be amplified by a valve system. These four methods of linkage may be called the loose contact (telephone transmitter), moving iron (telephone receiver), moving coil (loud speaker), and condenser (broadcasting transmitter) methods.

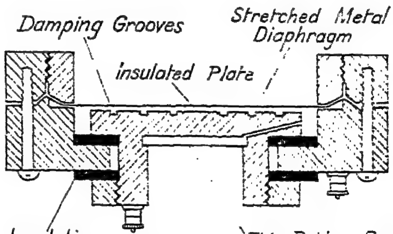


Fig. 123.—Wente's Condenser Microphone

Making of a Record.

We are now in a position to consider the changes which have recently come about in record production. In the old direct method of recording, the wax record had to be cut by a tool, for the movement of which only the energy of the human voice or the musical instrument was available. Even when a horn was used with a view to collecting the energy and concentrating it on a diaphragm, the amount available was very small. Singers had to perform close to the horn, and performers in an orchestra had to be crowded up close to one another and close

Fig. 124.—Sir Harry Lauder recording at Hayes; mechanical method

Fig. 125.—Sir Harry Lauder recording at Hayes; electrical method

to the horn (fig. 124). This caused all sorts of difficulties in musical balance and psychological difficulties with the performers. The method of electrical recording obviates all this. The sound waves are received on a microphone, which is a condenser transmitter. This form of microphone has the great advantage that it gives a very uniform response, i.e. the electrical energy developed bears a nearly constant ratio to the sound energy received both for high-pitched and for low-pitched notes. By the use of valve amplifiers this energy may be enormously amplified before it is applied to the cutting tool. This means that we can afford to be satisfied with a comparatively small amount of sound energy, so that the singer or speaker need not be unduly near the microphone, and the orchestra may be placed in their natural and accustomed positions at the other end of the room in which they are being recorded (fig. 125). Also the performance may be in a hall, and the recording may be done in a room at some distance.

A soft wax disc is faced as shown in figs. 126 and 127, and is placed on the recording instrument. A controlled needle is placed in position on the revolving wax, and would, if no sound were being recorded, describe a spiral. Under the influence of the sound, however, it oscillates from side to side, cutting a wavy line instead of a true spiral. The record so produced might be used with an ordinary sound box to reproduce the recorded sounds, but the wax would deteriorate rapidly under the needle, and so the original record is only played if it is desired to ascertain whether the conditions of recording are satisfactory. In any case, several of these originals are made with a view to selecting the best. The wax record is next prepared for electroplating. The surface is made conducting or metallized by coating with graphite, as shown in fig. 128, the deposited copper reproducing faithfully every detail of the trace upon the wax. The shell so produced is a negative, in which the depressions on the wax appear as elevations. It could, therefore, be used to press a record, but this might cause serious damage to this master shell. It is therefore specially prepared by a secret process, placed in another electroplating bath, and copper is deposited on its surface. When this copper has grown to a sufficient thickness it can be removed from the negative shell without injury to either, and the result is the mother shell, a positive record reproducing exactly the form of the original wax and capable of being played with a fibre needle, although easily damaged by a steel needle. The mother shell is now used to produce in an exactly similar way a further negative shell known as the working matrix. This shell after nickel-plating is prepared and mounted on a heavy copper disc, and the central hole is accurately bored. Matrices, having been prepared for each side of the record, are fixed into position in the top and bottom of a hydraulic press, on plates which can be alternately heated and cooled. A pin projects through the centre hole of the lower matrix to keep

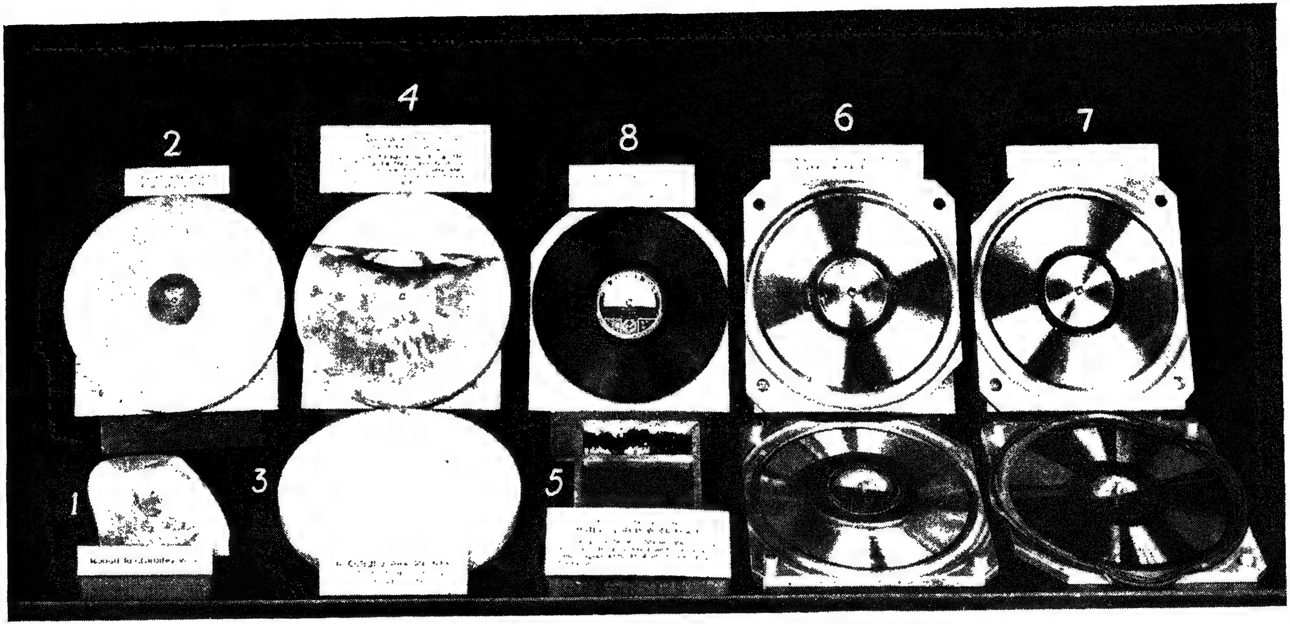


Fig. 126.—Stages in the manufacture of a record

1, Lump of recording wax. 2, Faced wax ready for recording. 3, Recorded wax showing shavings developed. 4, Recorded wax after removal from electro-plating bath, showing electro-deposited shell partly stripped. 5, Shellac and record material in powder form. 6, Lump of record material with label placed in lower mould plate. Upper mould plate shown above. 7, Mould plates separated after pressing. 8, Finished record after the edges have been ground and polished.

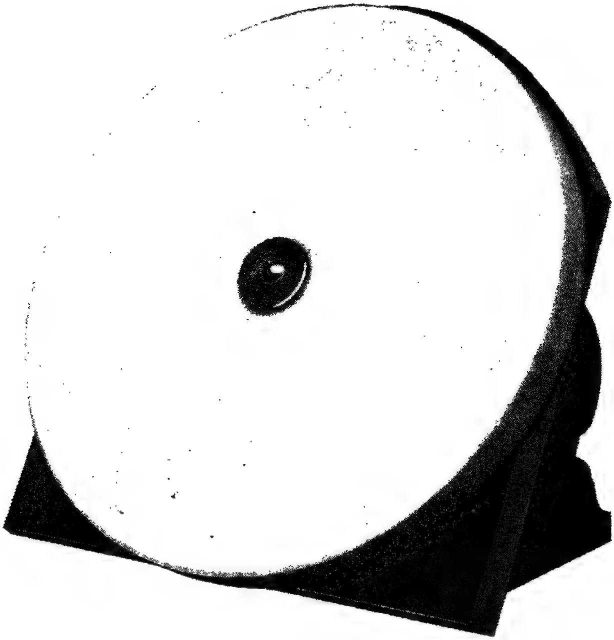


Fig. 127.—Faced wax disc ready for recording

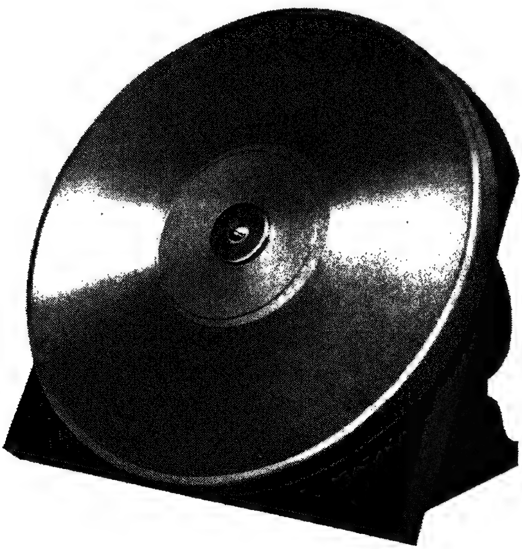


Fig. 128.—Wax record coated with graphite ready for electro-deposition of copper

clear the centre hole in the record. Record biscuit material is placed on a hot table and softened to the desired plasticity. Labels are held in position on the top and bottom matrices, and the material is rolled into a lump and placed in position over the centre pin. The press is closed and hydraulic pressure applied, cold water being fed through the plates until the record is sufficiently cooled. The record is then removed, tested, the edge polished, and if it is satisfactory passed to stock.

Reproduction from Record.

With regard to reproduction from the record, the advantages of using electrical power are less obvious. The source of energy for reproduction is the coiling of the spring when the gramophone is wound up, released as kinetic energy of rotation of the record. This energy is communicated to the needle point, and from the needle point to the diaphragm in the sound box by a lever arm seen in fig. 129. The movement of the needle from side to side as it traverses the spiral groove on the record produces a corresponding movement of the diaphragm in the sound box, and this in turn generates the sound waves in the air. If the diaphragm were directly exposed to the air, very little sound would be heard. The air would circulate as in the case discussed in an earlier lecture, but would not be subjected to changes of pressure; but by making the diaphragm one side of a box with a small aperture in the opposite side, the arrangement becomes a kind of velocity transformer. When the diaphragm is moving inwards air is forced out through the hole, and if the area of the diaphragm is considerably larger than that of the hole, the velocity of air through the hole must be considerably greater than the velocity of the air just in front of the diaphragm. In order to give the air this large velocity a pressure must be developed, and it is in this way that the sound box produces differences of pressure sufficiently great to give rise to easily audible sounds.

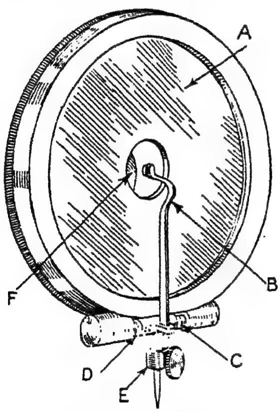


Fig. 129.—Sound Box

; B,
D, p
the stylus-bar rocks; E, needle socket; F, outlet communicating with tone-arm.

The Horn.

Looked at from another point of view, the pressure developed in the sound box opposes the motion of the diaphragm, and in its motion the diaphragm has to do work on the air. The greater the pressures

developed, the larger is the amount of energy transformed from the energy of rotation of the record to the energy of sound waves. The loudness developed, however, is still not nearly great enough for modern requirements, and it is necessary to attach to the sound box a horn. The function of the horn was at first completely misunderstood, and its use gave rise to considerable difficulties. The addition of the horn, preventing free expansion of air at the opening of the

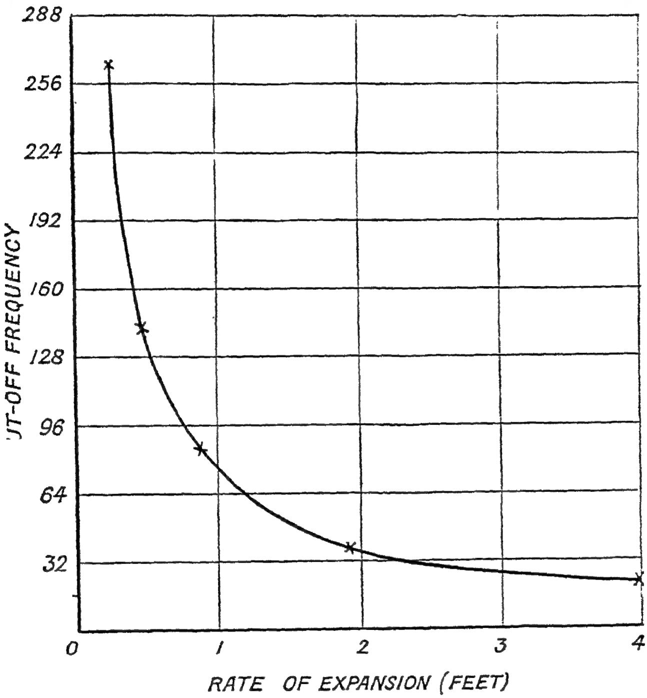


Fig. 130. Ordinates represent the lowest frequency efficiently radiated; abscissæ represent the increment of distance along the axis of the horn in which the area is doubled

sound box, increased the pressures developed and therefore increased the useful work done on the air by the diaphragm. It is analogous both to a transformer and to a transmission line in electrical engineering but it must be carefully designed. If it is short and ends with a comparatively narrow open end, the large pressure variations developed at the opening of the sound box are fairly well maintained, but considerable reflection takes place at the open end and the amount of sound radiated is small. On the other hand, if the horn is short and has a wide open end, the pressures developed at the opening of the sound box are less and the energy communicated by the diaphragm to the air is

correspondingly less. Thus we should expect a long horn to be desirable. A horn is also apt to introduce resonances due to its proper tone and partial tones, and this affects the evenness of the response of the gramophone, exaggerating certain notes above the general level of tone.

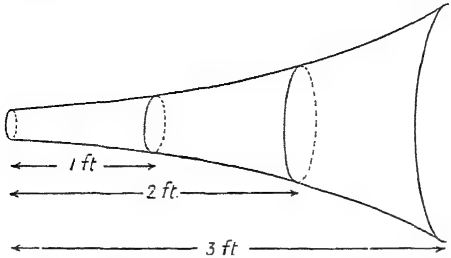


Fig. 131.—Exponential horn with rate of expansion 1 foot, i.e. area of cross section doubles for each increment of 1 foot measured along the axis.

It has been shown that the best form of horn is the exponential or logarithmic horn, which may be defined as one which doubles its area of cross section at equal distances along the axis. The lowest frequency which the horn will radiate uniformly depends on its rate of

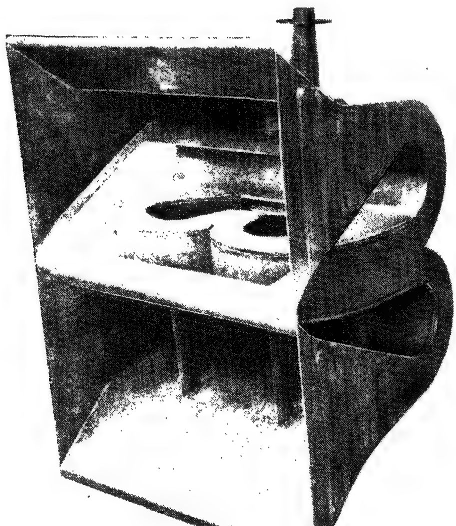


Fig. 132.—Section showing folded horn

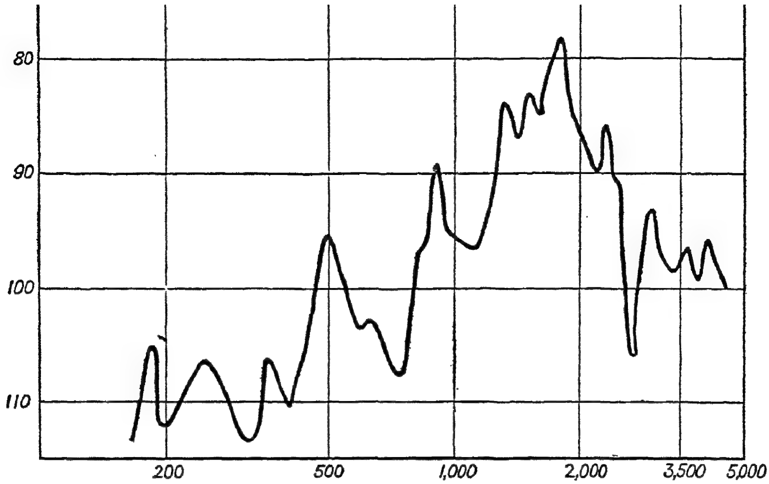
expansion, and the relation between the two is shown in fig. 130. If the area of the throat or narrow end of the horn is $\frac{1}{2}$ sq. in., the area 1 ft. from the end 1 sq. in., the area 2ft. from the end 2 sq. in., the area 3 ft. from the end 4 sq. in., and so on, we have the kind of horn shown

to scale in fig. 131. This horn cuts off at a frequency of just over 64. One expanding less rapidly cuts off at a lower frequency and vice versa. On the other hand, to prevent excessive reflection at the open end, the area there must be such that the diameter is at least equal to one-quarter of the wave-length for the lowest tone which it is desired to radiate. If, therefore, we wish to get down to a frequency of 64, the diameter of the open end must be about $4\frac{1}{2}$ ft. This corresponds to an area of about 16 sq. ft., and as the area must double every foot and we start with an area of $\frac{1}{2}$ sq. in., we shall find that the length of horn required is about 11 ft. The difficulty of combining this length of horn with compactness has been met by designing a folded horn which can be introduced into a comparatively small space as in the cabinet type of gramophone (fig. 132).

Measurement of the Performance of a Gramophone.

As a matter of fact, very few gramophones are designed to give uniform radiation to such a low frequency. The weakness in the bass in many gramophones is a notable feature, and now we are not dependent on judgments by ear but can actually test the performance and register at the same time the enormous improvements which have taken place. A gramophone record is cut for a pure tone of constant intensity. This record is then played by the gramophone under test in front of a condenser microphone. Measurement of the electrical voltage amplitude enables us to gauge the sound energy communicated to the air. By having a series of such records we are able to compare the sound output at various frequencies. One serious difficulty in the way of applying the method is the formation of standing waves in the room in which the test is carried out. Interference maxima and minima, the existence of which is hardly noticeable in the ordinary performance of music, at once become obvious with a pure tone. If I now put on one of these records for a high frequency note, in which case the maxima and minima of sound in the room will lie pretty close to one another, you will all find it quite easy, by closing one ear and moving the head, to detect the large and rapid variations in loudness which indicate the distribution of these maxima and minima. They are due to the reflection of sound from the surfaces in the room, and can be largely minimized by covering these with absorbent material; but it is almost impossible completely to eliminate them, and the loudness is averaged in actual practice by suspending the microphone and swinging it as a pendulum during the taking of the observations.

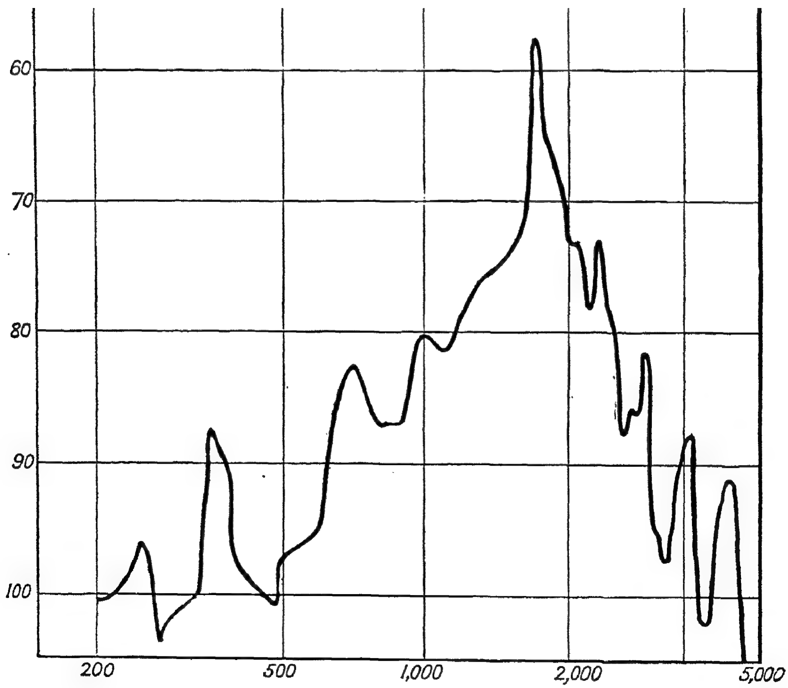
Figs. 133, 134, and 135 show the actual record for certain H.M.V. models, and some features invite comment. The curves are plotted so as to show the number of units of loudness which must be added to a sound of the given frequency in order to bring it up to a standard loudness. All the curves show peaks and depressions due to resonances



Frequency in cycles per second

Fig. 133

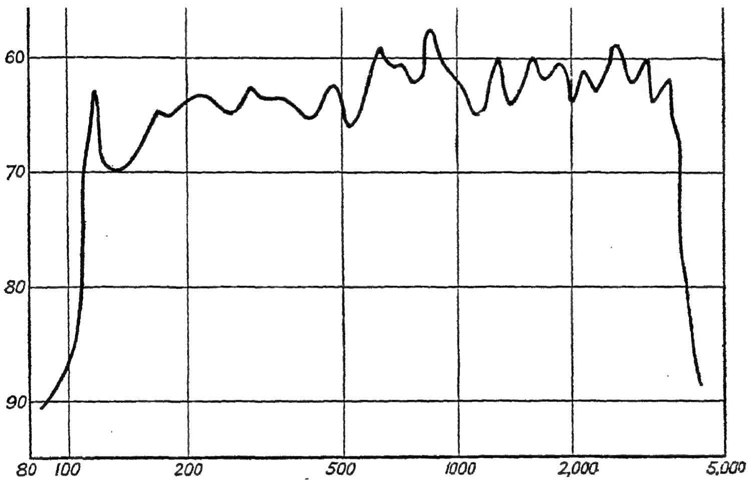
Distance of curve from axis indicates the loudness at the corresponding frequency. The numbers on the scale of ordinates represent the number of units of loudness required to bring the sound up to a standard loudness.



Frequency in cycles per second

Fig. 134

of the diaphragm, sound box, or some part of the apparatus, but the progress from a pointed curve to a flat-topped one is obvious, and it ought to be borne in mind that the ear is fairly tolerant, and that what the microphone reveals as a response varying with frequency would seem to the ear a fairly uniform response. The gradual extension of the range, both as regards lower and higher frequencies, can also be traced. In the case of the lower limit particularly, the ear again comes to the rescue of the mechanism. Notes can certainly be heard in the reproduction by some gramophones which are too low in pitch to be reproduced with any appreciable loudness. This raises an interesting



Frequency in cycles per second
Fig. 135

problem, and there is no reasonable doubt that the solution is to be found in the existence of difference tones produced in the ear itself.

It has been shown by Fletcher that, when the ear is exposed to a musical note consisting of a fundamental and its series of partial tones, the quality but not the pitch of the sound is altered by cutting out the fundamental altogether and even the next partial. This means that we hear a frequency which is not actually being produced in the air outside the ear. Remembering, however, that the ear is a structure capable of giving difference tones, and that the difference tone corresponding to any pair of consecutive partials in a musical note is the fundamental, we can see that the reason why some gramophones have given even a tolerable performance in the bass is due to the fact that the ear has supplied the notes, which so far as the reproduction by the gramophone was concerned were almost entirely absent.

Electrical Reproduction.

Gramophones, if used in ordinary rooms, do not require to be capable of very great loudness, and indeed excessive loudness is a disadvantage. On the other hand, if they are required for public performance in a hall, either to supply dance music or otherwise, the energy derived from the rotation of the record is insufficient for the purpose, and here electrical reproduction is useful. There is something to be said for the flexibility which it gives, even in the case where no

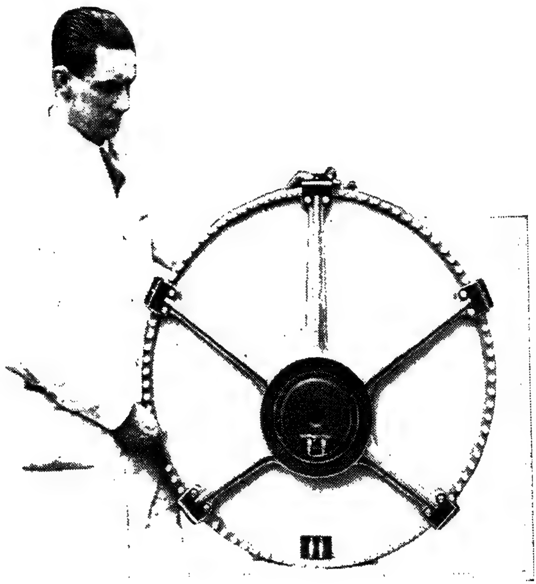


Fig. 136.—Loud-speaker of moving-coil type, consisting of large aluminium diaphragm with coil in eccentric position

great loudness is required, but it becomes essential in the cases we have indicated. For electrical reproduction the sound box and horn disappear, and we substitute instead a pick-up, amplifier, and loud-speaker. We have here an M.H.V. Model, No. 600. The pick-up is a microphone of the moving-iron type, in which the iron is moved in front of the poles of a magnet surrounded by a coil, not by the pressure waves due to the voice, but by the movement of the gramophone needle as it traces out its spiral groove. The electrical currents so produced are amplified in the usual way and delivered to a loud-speaker (fig. 136). This loud-speaker is designed without a horn with a view to greater uniformity of response. It consists of a very thin aluminium sheet stretched almost to its elastic limit, and clamped under tension to a

ring of diameter about 30 in. Attached to the diaphragm at some distance from the centre is a coil, this eccentric position being designed with a view to eliminating possible resonances of the diaphragm. The current from the amplifier traverses the coil, which is placed in the neighbourhood of a field magnet, so that the loud-speaker is really of the moving-coil type. It gives a response, extending down to frequencies of about 50 and up to frequencies of about 5000, with an almost uniform response between 100 and 4000.

Frequency and Articulation.

This range gives extremely good reproduction, both of speech and of music. The lower frequency limit is set to some extent by the record. The amplitude of the needle movement varies inversely as the frequency for equal intensity of pure tones. Thus, if very low frequencies are to be reproduced with the same energy, the amplitude will become so great that the cutting tool will pass into the next groove. For high frequencies a similar limit is set by the fact that the wavy trace consists of a series of very sharp turns, which produce a great tendency for the needle to jump instead of following the trace. It is also true that as the surface noise or scratch has some very high components, we may lose more in musical effect by accentuating this than we gain by bringing in the very high components of the music, and so an extension in this direction may be undesirable, at least until some method of reducing or eliminating the scratch is devised. Broadly speaking, we may say that a frequency range from 500 to 2500 gives good-quality speech, but dull and colourless music. Good reproduction of music requires a range of from 50 to 5000 at least. The importance of various parts of this range may be made clear by introducing into the loud-speaker circuit an electric filter, by means of which we can cut out the electrical components of either high or low frequency, and find the effect of this on the reproduction.

The Gramophone Company have kindly supplied us with one of these filters, and the effect can be well judged on the record which reproduces Beatrice Harrison with her 'cello inducing the nightingales to sing. Cutting out the low frequencies we hear only the birds; cutting out the high frequencies the 'cello predominates. Even more instructive is the application of the filter to the record in which Harry Lauder sings " Off the Chain ", and introduces his famous patter between the verses. Cutting out the low frequencies we find the volume of sound enormously reduced, and the quality of Harry Lauder's performance suffers acutely, but the words remain quite intelligible and we can understand most of what is said. On the other hand, if we cut out the high frequencies we produce very little effect on the volume of sound and on the quality, but all possibility of understanding the words disappears.

Fig. 137 shows the results of careful experiments on the variation of energy and articulation produced by varying the region of frequencies cut out. Articulation was tested by reproducing a series of syllables and estimating the percentage correctly noted by an observer. It will be noticed that a filter which eliminates all the frequencies below 500 eliminates 60 per cent of the energy in speech, but only reduces the articulation by 2 per cent. The bulk of the energy exists as a matter of fact in components of frequency about 200, but these components have a minimum articulation value. On the other hand, it will be noticed that a filter which eliminates all the frequencies

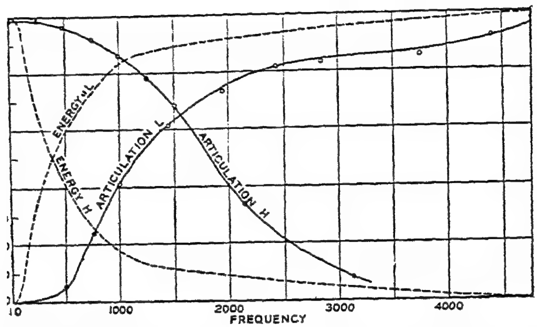


Fig. 137.—Effect upon the articulation and energy of speech of eliminating certain frequency regions

The point where the energy H curve cuts a given ordinate indicates the percentage energy transmitted when all frequencies below that of the ordinate are cut off; the point where the articulation H curve cuts an ordinate indicates the percentage articulation if all frequencies below that of the ordinate are cut off; conversely for the curves energy L and articulation L.

above 1500 eliminates only 10 per cent of the energy, but reduces the articulation 35 per cent. The two articulation curves intersect on the frequency 1550 and at 65 per cent articulation, which shows that whether we cut off all frequencies below 1550 or all frequencies above 1550, the effect on the articulation is the same and reduces it by 35 per cent, although in one case we cut off about 90 per cent of the energy and in the other case only about 10 per cent.

Recording on Film.

We must now turn our attention to the matter of recording on film. Here we have to deal with some method of modifying the light falling on a sensitive surface in such a way that the modifications will correspond to a succession of sounds and be reproducible as a succession of sounds. An illuminated slit is focused on a moving photographic film, and the illumination of the slit modified by the sounds to be recorded. This can be accomplished in one of two ways: either we may modify the brightness of the source of light which is illuminating the

slit, or else we may modify the beam of light after it has left the source. Early experimenters attempted to develop the first method.

In 1901 Ruhmer used the carbon arc for this purpose. The currents from a microphone were introduced into the circuit of the arc from a transformer, and the modifications of the current from the arc so obtained altered its brightness and so the brightness of illumination of the slit whose image was being thrown on the moving film. In this way there was produced on the film a band of variable density, the variations corresponding to the variations in current delivered by the microphone, and so to the variations in pressure of the sound waves received by the microphone. In his account of his experiments he clearly anticipates the talking film, but he does not appear to have achieved much success in this direction. As a matter of fact, small variation of current in the circuit of the arc can only produce small changes in brightness of a very bright source, and as the carbons retain heat and cool comparatively slowly, they can hardly be expected to follow the changes of current with the rapidity necessary for recording high frequencies. More success has been achieved by substituting the mercury arc for a carbon arc, the mercury being contained in a quartz tube in which a gap in the column is produced after the current is established. An electric discharge tube containing neon gas at very low pressure has also been used, and here the fluctuations in brightness are greater and more rapid. These can be illustrated by the simple piece of apparatus provided for us by the Gramophone Company (fig. 138). The neon discharge tube is made to rotate rapidly in a vertical circle about an axis near one end. It is connected up to a microphone, and you will notice the interesting patterns produced by rapid variations in brightness as I recite into the microphone the well-known song written in praise of Pooh.

Instead of varying the brightness of the source we may, however, modify in some way the beam of light after it has left the source. This can be done in several ways, some of which involve the use of plane polarized light, the plane of polarization of which is rotated by a varying magnetic or electric field supplied by the microphone. A quite simple method is the interposition of an oscillograph controlled by the microphone, so that the light from the source is reflected on to the slit by the mirror of the oscillograph. This is arranged so that a greater or less length of slit is illuminated, according to the current variations produced in the microphone. The record produced by the first general method described will appear as shown in fig. 140, the intensity at any point being uniform across the width of the band. The record produced by the method just described will appear as a uniformly bright band of varying width (fig. 139).

For application to a talking film the latter method has certain obvious advantages. It allows the use of a very bright source, and

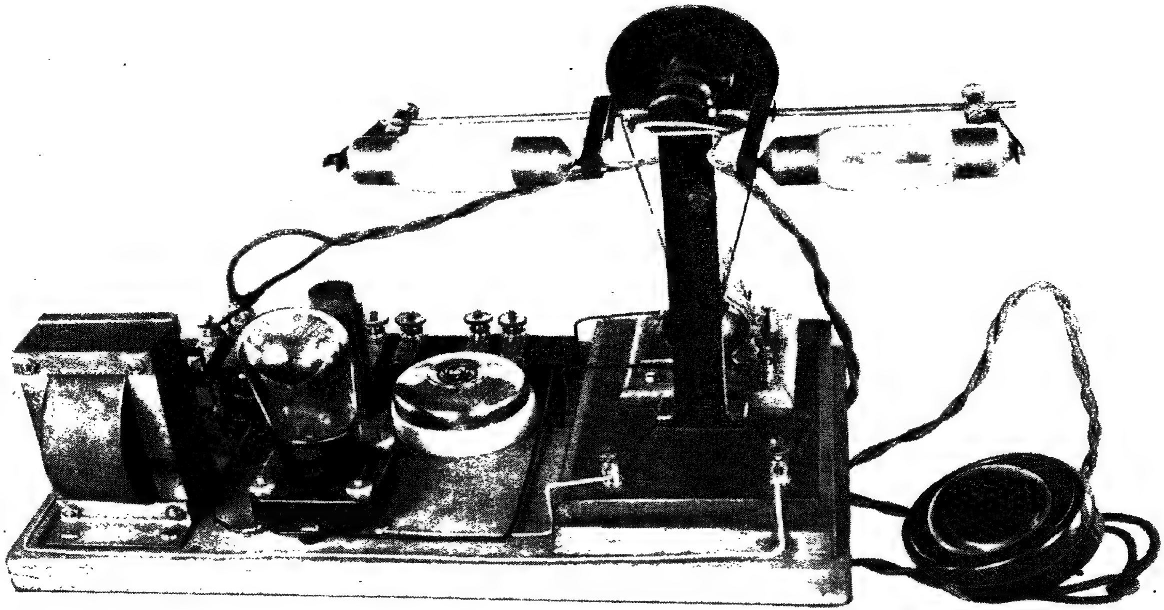


Fig. 138.—Rotating Neon Tube

The electric discharge in the tubes is modified by the vibrations due to the voice speaking into the microphone. These modifications of intensity produce very beautiful patterns owing to the persistence of vision when the tubes are rotated.

when we consider that it is desirable to register frequencies up to 5000 per second, it will be obvious that if any actinic effect is to be produced on the film in the very short exposures possible we ought to use a bright source. The method also makes it possible to vary the light on the slit from zero to its maximum value, instead of giving a small variation in brightness superimposed on a uniform brightness. The record for talking film purposes is produced on the edge of the film carrying the pictures. The width of this is about 1 in., $\frac{9}{10}$ being devoted

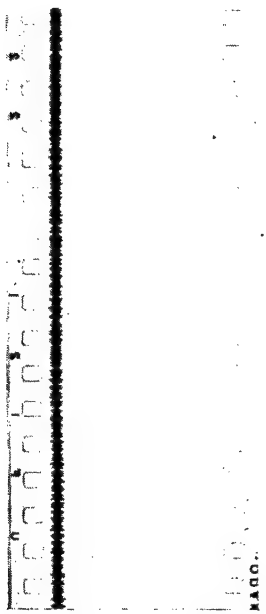


Fig. 139.—Sound record produced by constant intensity of source, giving band of varying width.

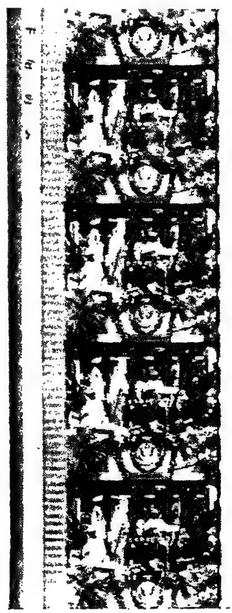


Fig. 140.—Sound record produced by variable intensity of source with constant width of slit. The sound record is immediately to the left of the picture.

to the pictures and $\frac{1}{10}$ to the sound record. The illuminating slit has to be very narrow, as the speed of the film is now standardized for picture purposes at about 40 cm. per second. If a frequency of 5000 is to be recorded, the width of the image of the slit on the film must not exceed $40/5000 = \cdot 008$ cm.

Reproduction from Film.

We now have to consider the process by which the sounds are reproduced from the film. The film passes in front of a slit illuminated by a constant source, and we shall then have on the farther side of the slit a light beam which will reproduce more or less closely the varia-

tions in brightness of the original beam. The problem is to transform these variations in brightness of a beam of light into variations of the pressure of the air. Earlier attempts made use of the element selenium. The electrical resistance of this element varies with the light incident on it, so that if our variable beam is allowed to fall on a selenium cell included in a circuit, the variations of resistance will cause variations of current which can be amplified and delivered to a loud-speaker. This method is still in use, although some experimenters find the selenium too slow in its response for high-frequency reproduction.

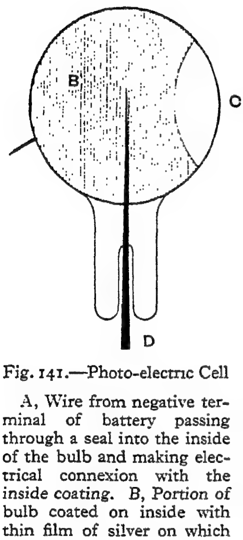


Fig. 141.—Photo-electric Cell

A, Wire from negative terminal of battery passing through a seal into the inside of the bulb and making electrical connexion with the inside coating. B, Portion of bulb coated on inside with thin film of silver on which

trons are emitted. C, Transparent portion of bulb through which the light falls on the alkali metal. D, Electrode passing up into interior of bulb and connected to positive electrode of battery.

The method more commonly used is that of the photo-electric cell. In 1888 Hallwachs found that if light fell on a clean zinc surface, negative electrons were emitted by the zinc. Other metals, particularly the alkali metals, show the same effect. A photo-electric cell commonly consists of a glass bulb about $2\frac{1}{2}$ in. in diameter as shown in fig. 141. The interior surface is coated with a fine deposit of silver, except over an area about $1\frac{1}{2}$ in. in diameter on one side. The silver deposit is covered with a deposit of the metal used, and this is placed in metallic contact with a wire entering through the seal. The light is admitted through the unsilvered side of the bulb, and the silver on the other side acts as a reflector and also facilitates metallic contact between the alkali metal and the wire. Another wire acts as the second electrode. The bulb is exhausted, and the alkali metal connected to the negative pole of a battery and the second electrode to the positive pole. In the dark no current can pass, but if light is allowed to fall on the bulb negative electrons are emitted from the alkali metal and move to the positively charged wire, so that a current flows in the circuit, whose intensity varies with the intensity of the light. The bulb is either highly exhausted or else contains a slight trace of an inactive gas such as neon. The function of the gas is to amplify the effect, as the negative electrons emitted from the alkali metal ionize the gas molecules by collision into positive and negative ions, so that as a result of one ionizing collision we have two negative ions and one positive one available for carrying current instead of the single negative electron originally emitted.

This type of cell has many applications. It can be used as a photometer for measuring light intensity, and is a method of transforming

variations in light intensity into variations of electric current. It has its use not only in reproducing from the talking film but also in television.

The rest of the process will now be clear. The film is passed between a strongly illuminated slit and the photo-electric cell and the resulting currents are amplified and delivered to a loud-speaker. The success of the process you can judge for yourselves. At the end of the lecture we shall put through the apparatus two lengths of film. One of these is a talk by Dr. Richmond of Union College, Schenectady, on "The Potentialities of the Talking Film". The other is a portion of an experimental lecture by Dr. Langmuir of the General Electrical Company's Laboratory, Schenectady, on "Mono-molecular Films on the Surface of Water". We are extremely fortunate in having two of Dr. Langmuir's students here, and they have kindly arranged the demonstration. Whatever may be the future of the talking film as a means of entertainment, I think the demonstration will leave on our minds no doubt that as a method of instruction it has features of very great value. Not only is the reproduction extremely realistic, but the way in which the two lecturers get their personalities across is remarkable. The use of the method of the "close-up" as a way of showing an experimental illustration or a diagram from a book or a mathematical expression on the black-board is extremely convenient, and in the case of the experiments enables the whole audience to see the details of an experiment much better than was possible to any except a very few in the original lecture. If the masters of experimental lecturing can be thus recorded and reproduced at will, the method ought to do much not only for scientific instruction but for the stimulation of general scientific interest.

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